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INDIANA
DEPARTMENT OF TRANSPORTATION

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WA/IN/JHRP-89/11

:cutive Summary, Vol. 4

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HABILITATION AND REPLACEMENT
HIGHWAY BRIDGES, FINAL
PORT VOL. 4: COST ANALYSIS

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JOINT HIGHWAY RESEARCH PROJECT

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Executive Summary, Vol. 4

THE DEVELOPMENT OF OPTIMAL STRATEGIES FOR MAINTENANCE, REHABILITATION AND REPLACEMENT OF HIGHWAY BRIDGES, FINAL REPORT VOL. 4: COST ANALYSIS

Mitsuru Saito
Kumares C. Sinha

FINAL REPORT

The Development of Optimal Strategies for Maintenance Rehabilitation and Replacement of Highway Bridges, Final Report Vol. 4: Cost Analysis

Executive Summary

TO:	Harold L. Michael, Director Joint Highway Research Project	August 15, 1989 Revised October 5, 1990 Project: C-36-73I
FROM:	Kumares C. Sinha, Research Engineer Joint Highway Research Project	File: 3-4-10

Attached is the Vol. 4 of the Final Report on the HPR Part II Study entitled, "The Development of Optimal Strategies for Maintenance Rehabilitation and Replacement of Highway Bridges." This volume provides a detailed cost analysis of maintenance, rehabilitation and replacement projects in Indiana. An analysis of timings of bridge improvement projects is also discussed. The use of the information in a life cycle cost approach of project evaluation is presented. The research was conducted under my direction.

This report is forwarded for review, comment and acceptance by the InDOT and FHWA as partial fulfillment of the objectives of the research.

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FINAL REPORT

The Development of Optimal Strategies for Maintenance, Rehabilitation and Replacement of Highway Bridges, Final Report Vol 4: Cost Analysis

Executive Summary

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Prepared as Part of an Investigation

Conducted by

Joint Highway Research Project
Engineering Experiment Station
Purdue University

in cooperation with the

Indiana Department of Transportation

and the

U.S. Department of Transportation
Federal Highway Administration

Purdue University
West Lafayette, IN 47907
August 15, 1989
Revised October 5, 1990

TECHNICAL REPORT STANDARD TITLE PAGE

1. Report No. FHWA/IN/JHRP-89/11	2. Government Accession No.	3. Recipient's Catalog No.
4. Title and Subtitle The Development of Optimal Strategies for Maintenance, Rehabilitation and Replacement of Highway Bridges, Final Report Vol. 4: Cost Analysis		5. Report Date August 15, 1989 Revised October 5, 1990
		6. Performing Organization Code
7. Author(s) Mitsuru Saito and Kumares C. Sinha		8. Performing Organization Report No. JHRP-89/11
9. Performing Organization Name and Address Joint Highway Research Project Civil Engineering Building Purdue University West Lafayette, IN 47907		10. Work Unit No.
		11. Contract or Grant No. HPR-1(24) Part II
12. Sponsoring Agency Name and Address Indiana Department of Transportation State Office Building 100 North Senate Avenue Indianapolis, IN 46204		13. Type of Report and Period Covered Executive Summary Final Report Volume 4 of 6
		14. Sponsoring Agency Code

15. Supplementary Notes

Prepared in cooperation with the U.S. Department of Transportation, Federal Highway Administration

16. Abstract

This volume is the fourth of a six-volume final report and it presents analyses conducted to develop appropriate cost and timing estimates for various bridge related activities. A computer program was then written so that a life cycle cost analysis can be undertaken to select bridge improvement activities.

The titles of all six volumes are listed below:

Vol. 1. Elements of Indiana Bridge Management System

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17. Key Words Bridge Cost, Project Timing, Replacement Cost, Rehabilitation Cost, Maintenance Cost, Life Cycle Cost Analysis	18. Distribution Statement No restrictions. This document is available to the public through the National Technical Information Service, Springfield, Virginia 22161

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price
Unclassified	Unclassified		

Form DOT F 1700.7 (8-69)

The Development of Optimal Strategies for Maintenance, Rehabilitation and Replacement of Highway Bridges, Final Report Vol. 4: Cost Analysis

EXECUTIVE SUMMARY

As part of a study to develop a network level bridge management system for the Indiana Department of Transportation (INDOT), a series of analyses was performed on unit cost and timing of bridge replacement, rehabilitation and maintenance. A life cycle cost model was also developed for various bridge activities. This report describes the methodologies and results of the analyses. The analyses consisted of the following three parts:

1. Analysis of bridge replacement, rehabilitation and maintenance costs;

2. Timing for replacement, rehabilitation and maintenance activities;

3. Life cycle cost analysis.

The analysis of variance (ANOVA) approach and the regression method were applied to develop the cost prediction models of various bridge activities. Unit replacement costs were established separately for concrete and steel bridges, as a function of such factors as bridge type, deck size and so on. The values developed in the study are considered to be more precise than the currently used average cost values. They can be used to make initial estimates of future expenditures for a bridge. The unit costs of deck, superstructure and substructure were studied separately. As for rehabilitation alternatives, two major activities were considered for analysis: deck reconstruction and deck replacement. These two activities are the primary bridge rehabilitation alternatives in Indiana. Appropriate values for routine bridge

maintenance costs were also developed. Figures 1 and 2 present some examples of the study results.

For life cycle cost analysis, a reasonable estimate of the timing for future bridge repair activities is essential. Estimates of timing for various activities were established on the basis of historical records of condition ratings at which such activities were recommended. The statewide average bridge age at replacement was found to be approximately 52 years. INDOT currently uses 50 years as the average bridge service life. It should be noted, however, that not all bridge replacements in the past were necessarily undertaken at the time the bridges were in need of replacement. A statistical analysis conducted in the study showed that the perceived bridge service lives with and without rehabilitation was significant. As for rehabilitation alternatives, the first deck reconstruction would take place, on the average, about 20 years after the initial construction of a bridge. Deck replacement on the other hand would take place at about 46 years. The results of the timing study would provide an overall guideline as to bridge activity profiles, and therefore, help bridge managers to conduct a realistic life-cycle cost analysis.

A procedure to perform a life-cycle cost analysis on bridge improvement options is also discussed in this report. Because bridges are a long-term multi-year investment, the consideration of life cycle costs is essential to evaluate the economic desirability of an option over the others. Throughout its useful life, a bridge requires both routine and periodic maintenance and occasional rehabilitation works. As a bridge eventually approaches the end of its useful life, it is scheduled for replacement. Bridges, thus, require a series of expenditures for various activities during their life cycles, as shown in Figure 3.

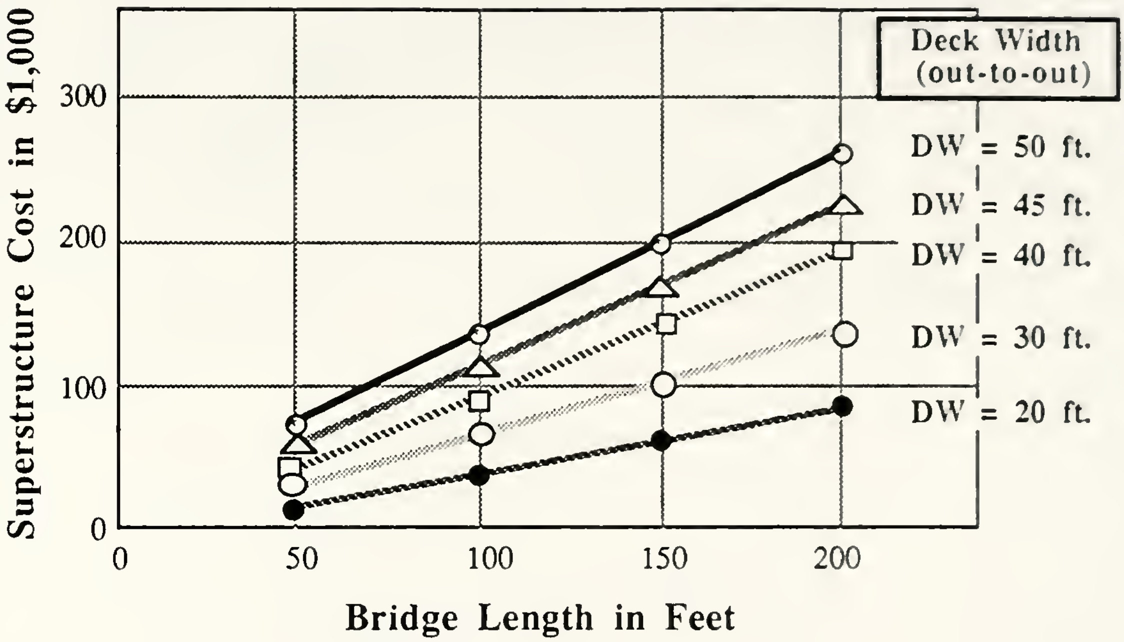
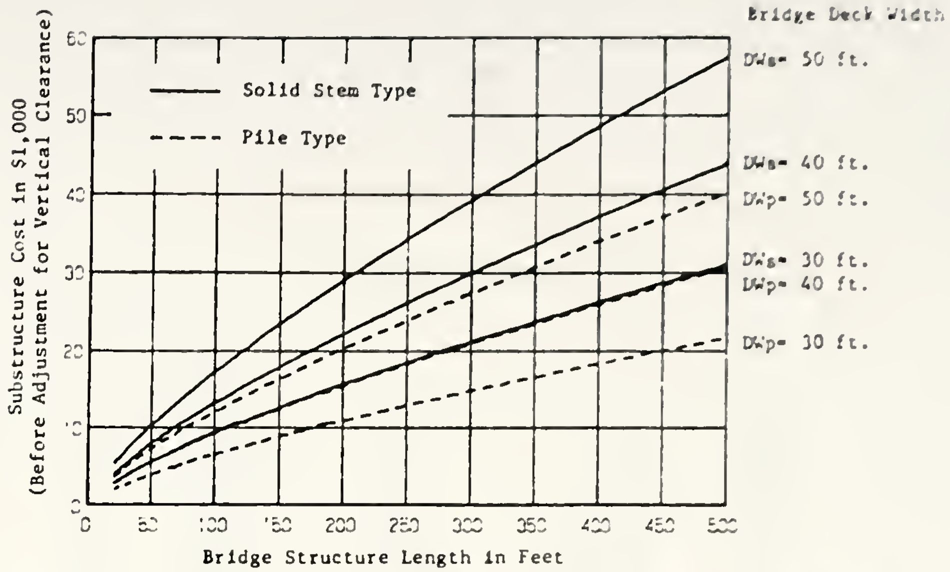
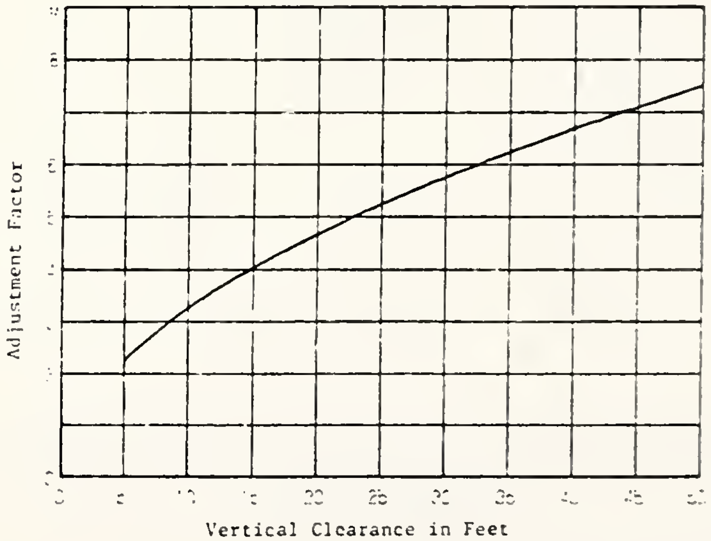


Figure 1. Predicted Superstructure Cost for RC-Slab and Box-Beam Bridges



(a) Substructure Before Adjustment for Vertical Clearance (in $1,000)



(b) Adjustment Factor for Vertical Clearance

Figure 2. Nomographs for Determining Substructure Cost

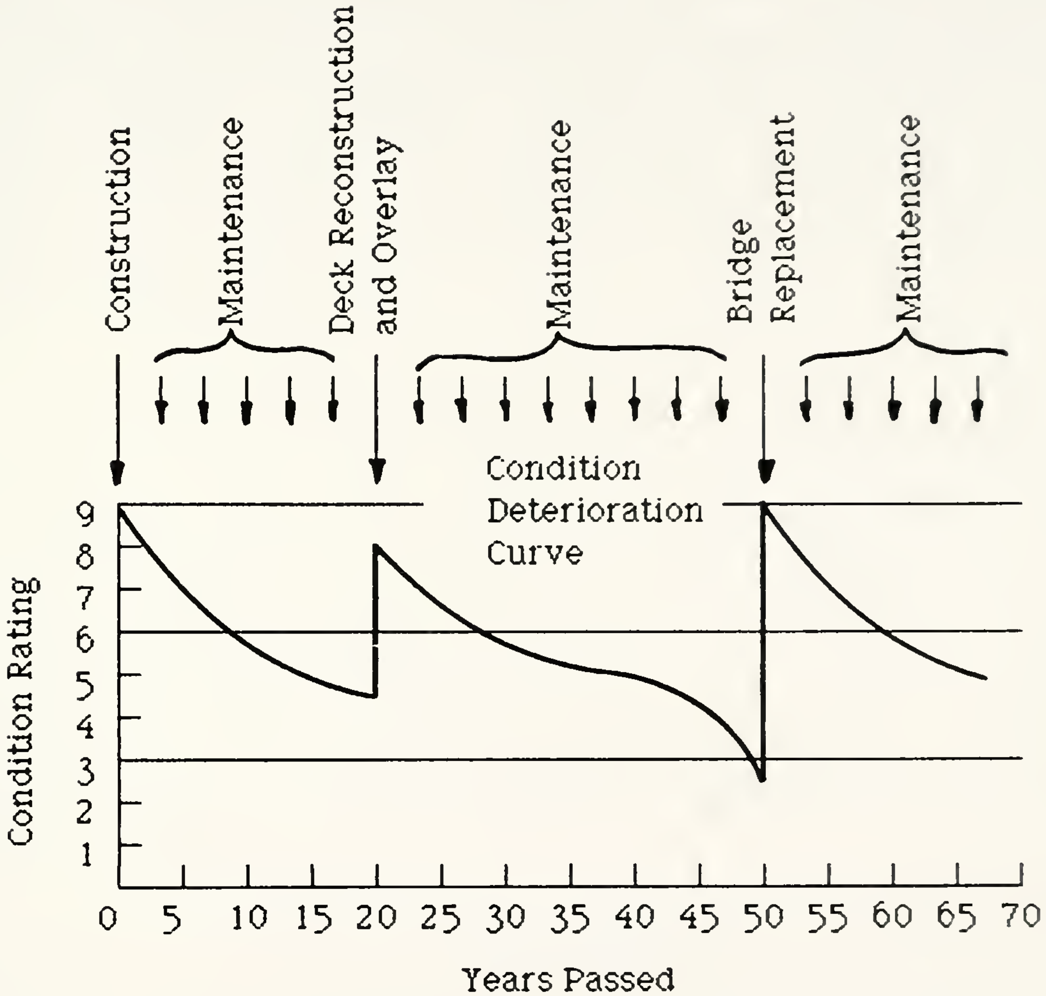


Figure 3. Life Cycle of a Bridge

The equivalent uniform annual cost (EUAC) method for perpetual service was used in the study. This method is especially suitable for evaluating multiple alternatives with different analysis periods. For selecting a group of least cost options from different bridge locations, equivalent uniform annual costs need to be converted to commensurable values. For this purpose, bridge traffic volumes were used as a weighing factor. The factor indicates the number of vehicles benefited for each dollar spent for a bridge activity. A computer program for cost estimation and life cycle cost was coded to facilitate the economic analysis.

All the analyses discussed in this report were performed with the data collected from the bridge records. Actual bid costs were used in the cost analyses and the results of different years were converted to the 1985 price using the construction price index of the FHWA related projects. The methodologies presented in this report contain the items necessary to make the bridge cost estimation more precise than the existing practice, and therefore, to provide better information for ranking and optimization models for bridge project selection.

JOINT HIGHWAY RESEARCH PROJECT

FHWA/IN/JHRP-89/11

Final Report, Vol. 4

THE DEVELOPMENT OF OPTIMAL STRATEGIES FOR MAINTENANCE, REHABILITATION AND REPLACEMENT OF HIGHWAY BRIDGES, FINAL REPORT VOL. 4: COST ANALYSIS

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FINAL REPORT

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19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price
Unclassified	Unclassified		

Form DOT F 1700.7 (8-69)

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

ACKNOWLEDGMENTS

The guidance and assistance of William T. Dittrich and Joseph S. Torkos of the Indiana Department of Transportation (INDOT) and Paul A. Hoffman of the Federal Highway Administration (FHWA) Divisional Office in conducting the study is gratefully acknowledged. The help of Steven Hull of INDOT in the early phase of the study is also acknowledged. The authors are thankful for the extensive review made by Robert E. Woods of the draft reports. Thanks are extended to James Hare of the FHWA Regional Office who served as the Field Project Advisor and John O'Fallon of the FHWA Structures Division who served as the Headquarters Technical Contact. The successful completion of the project owed greatly to the generous support of the district bridge inspectors of the INDOT. Acknowledgment is also extended to Mrs. Rita Pritchett and Mrs. Cheryl Kerker who typed the report.

CHAPTER 1

INTRODUCTION

1.1 Background

The present research was undertaken as a part of a study to develop a method to assess present and future maintenance, rehabilitation, and replacement needs of existing bridges and to develop optimal strategies for an effective management of bridge activities. The scope of the study was defined through discussions with bridge inspectors of the central office as well as the district offices of the Indiana Department of Transportation (INDOT). In broad terms, the study was divided into four sub-areas: consistency of condition ratings, analysis of bridge improvement costs and impacts, development of performance and needs assessment models, and development of project selection models. Data bases for this study were compiled from the existing bridge records obtained either from INDOT or the Federal Highway Administration's Washington office, and a series of interviews and questionnaire surveys of the bridge inspectors of the district offices and the central office of INDOT.

1.2 Purpose and Scope of Research

The goal of the overall study was the development of improved methods for the assessment of present and future needs of existing bridges in order to determine optimal strategies for the maintenance and preservation of the highway bridge system. The overall research purpose was broken down to several major objectives:

1. Development of a method to better use the existing bridge inspection data in selecting bridges for maintenance, rehabilitation, and replacement;

2. Development of a method to provide consistent and statewide uniform measurements for rating bridges;

3. Analysis of bridge maintenance, rehabilitation, and replacement costs, and analysis of relationships between bridge attributes and costs;

4. Development of a method to estimate remaining service life of bridges and effects of bridge activities on condition rating and service life;

5. Development of a bridge traffic safety evaluation scheme that relates physical characteristics of bridge structure to accident potential;

6. Development of a project selection procedure using life cycle cost analysis, ranking, and optimization methods; and

7. Development of a set of guidelines that can be used by the Indiana Department of Transportation in implementing a bridge management system including data bases and organizational requirements.

The items listed above are presented separately in different volumes. The present volume includes the following items:

1. Analysis of bridge maintenance, rehabilitation, and replacement costs and development of cost prediction models;

2. Determination of the timing for bridge replacement and rehabilitation activities;

3. Development of a life cycle cost analysis methodology that can be used for the Indiana Bridge Management System (IBMS).

1.3 Report Organization

This report consists of five chapters. Chapter 2 presents the results of detailed statistical analyses on costs of bridge maintenance, rehabilitation, and replacement. Chapter 3 contains the results of analyses on the timing of bridge replacement and rehabilitation activities. Chapter 4 describes the concept of life cycle cost analysis as applied to bridge management. The chapter presents an application of the equivalent uniform annual cost approach for perpetual services to compare multiple bridge work options. Chapter 5 gives the summary and conclusions of the research findings.

CHAPTER 2

ANALYSIS OF BRIDGE REPLACEMENT, REHABILITATION AND MAINTENANCE COSTS

2.1 Introduction

Making accurate cost estimates is an integral part of a bridge management system to assess present and future funding needs for bridge improvements. As part of a study to develop a network-level bridge management system for the Indiana Department of Transportation (INDOT), a series of statistical analyses were performed on bridge replacement, rehabilitation, and maintenance costs to develop a set of unit costs and cost prediction models. Because the IBMS is expected to provide assistance to the programming process, definitions of replacement, rehabilitation, and maintenance used in this study followed those described in the Biennial Highway Improvement Program published by INDOT. Replacement of a bridge signifies a replacement of the entire bridge structure including the approach construction. Rehabilitation indicates major repairs that are performed by private contractors. Maintenance of a bridge includes minor repairs and preventive works that are described in the Indiana Field Operations Handbook for Foremen [IDOH 1985-86]. Maintenance is usually undertaken by INDOT maintenance personnel.

Before any statistical analyses were conducted, replacement and rehabilitation costs were all converted to the 1985 price by using the FHWA construction price indices [BOC 1986]. As for maintenance, costs used for the fiscal year 1985-86 were used. In the statistical analyses, bridge related network management factors, such as highway type, climatic regions, traffic volume, and bridge type, were taken into account to test effects of these factors upon improvement costs. Especially, replacement cost prediction models were validated by using a set of newly replaced bridges. The models proved to be a promising tool to estimate future replacement costs. Data required for this study were collected from the bridge inspection records, improvement cost records, bridge work history files, and design plans available at InDOT.

Along with the cost analysis, timings of applying improvement actions were analyzed. Timings of improvement works are another factor needed for a life-cycle cost analysis of bridges. A reasonable estimate of the timing for future bridge repair expenditures is essential and it is more important than the exact number of years for which the repair is required to perform. Bridge condition ratings at the time when improvement alternatives were recommended by bridge inspectors were also investigated to find relationships between the timing of action and the condition rating at the time of improvement. Results of the these analyses were used not only for the life-cycle cost analysis but also for the dynamic programming optimization routine discussed in Volume 6 of this report.

This chapter presents procedures used to derive representative unit costs and to develop cost prediction models as well as the results of cost analyses. Unit costs established in this study are considered to be more precise than

the currently used average cost values. They can be readily used to make initial estimates of future expenditures for a bridge. For instance, replacement cost prediction models can be transformed into nomographs to construct quick reference cost charts. The following three sections present results of cost analyses of replacement, rehabilitation and maintenance work, respectively. As for rehabilitation alternatives, two major actions were considered for analysis: deck reconstruction and deck replacement. These two actions were found to be the most representative rehabilitation alternatives applied to bridges on the state highway system in Indiana.

2.2 Bridge Replacement Cost Analysis

2.2.1 Background

Bridge replacement costs account for a significant amount of the total highway improvement cost. Statistical analyses were performed in order to develop appropriate models for the estimation of future bridge replacement costs. The term "replacement" indicates a replacement of the entire bridge structure, as used in the Biennial Highway Improvement Program of the Indiana Department of Transportation. Two objectives were set for the replacement cost analysis. One objective was to develop a systematic method that can be used by bridge engineers and inspectors to make reasonably precise estimates of replacement costs of individual bridges. The other objective was to develop replacement prediction models which can be subsequently incorporated into a network level bridge management system.

In the analysis, two basic steps were used. First, the analysis of variance (ANOVA) approach was used to identify effects of management factors upon

unit costs of bridge components and total costs of bridge approach roads. Then, based on the results of ANOVA, cost prediction models were developed using the regression approach. The models were subsequently validated for their reliability. Prediction models were also developed separately for the bridge approach and the remaining all "other" costs as well as for the bridge structure costs such as superstructure and substructure costs.

2.2.2 Data Base

Only state-owned bridges, replaced from 1980 through 1985, were used for subsequent statistical analyses. As shown in Figure 2.1, two hundred and seventy-nine state-owned bridges were replaced during this period in Indiana. Currently, newly designed bridges are grouped into five types: concrete box beam, reinforced concrete slab, concrete I-beam, steel beam, and steel girder. Because only a few box beam bridges were constructed during this period, these bridges were grouped with reinforced concrete slab bridges. Replacement cost data were collected on items shown in Table 2.1. The records needed for this analysis were obtained from the Bridge Design Section of INDOT.

Cost data used in this analysis were actual bridge contract costs. Only major attributes characterizing bridges were selected as independent variables since this cost analysis was intended for developing simple yet reasonably accurate prediction models. These attributes included those parameters that bridge engineers and inspectors can readily relate to for describing bridges, such as bridge length, deck width, and vertical clearance. Replacement costs in different years were adjusted to the 1985 price using the FHWA construction price indices [BOC 1986]. Data obtained were examined for their suitability

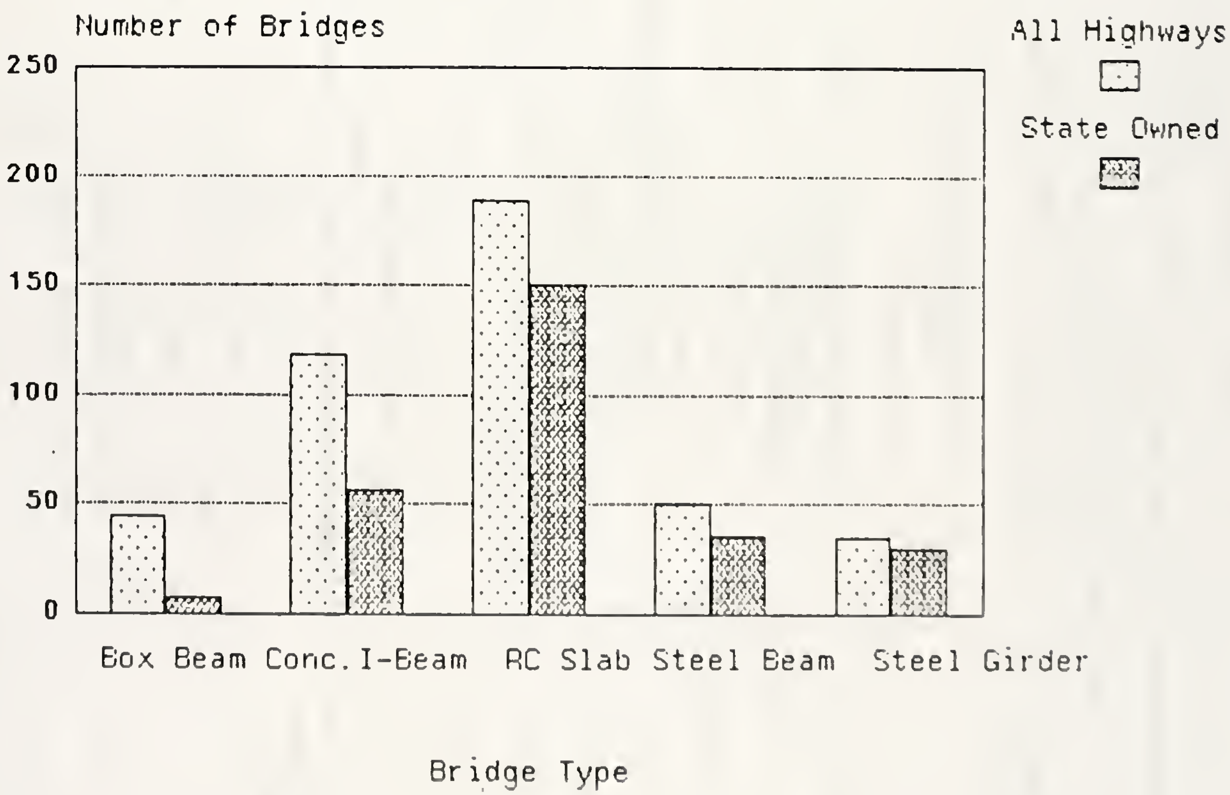


Figure 2.1 Number of Bridges Replaced From 1980 Through 1985 in Indiana

Table 2.1 Factors and Variables Considered for Replacement Cost Analysis

Classification Factors	1. Superstructure 2. Substructure 3. Highway Classification
Dependent Variables	1. Actual Costs A. Total Replacement Cost B. Cost Components a. Superstructure Cost b. Substructure Cost c. Approach Cost d. "Other" Cost * Other structure cost * Mobilization/demobilization cost * Traffic control cost * Demolition cost * Miscellaneous cost (field office, etc.) 2. Unit Costs * Unit Superstructure Cost * Unit Substructure Cost * Unit Total Structure Cost
Independent Variables	1. Bridge Structure Length 2. Bridge Deck Width (out-to-out) 3. Vertical Underclearance 4. Skew of the Superstructure 5. Number of Spans 6. Approach Roadway Length 7. Approach Roadway Width 8. Approach Roadway Earthwork

to subsequent analyses. It was found that some bridge construction contracts included two bridges together. Where it was difficult to separate costs for each bridge, such data were excluded from the input data set. Bridges with unnecessarily high or low costs relative to the normal range of construction costs, due to unusual site specific factors, were also excluded. Furthermore, there were a few bridges with no approach road length and they were not considered in the analysis. Their number was, however, very small.

2.2.3 Results of Preliminary Analyses

After preliminary analyses, it was found that predictions would be more reliable if some cost items had been grouped. For instance, the "other structure cost" item found in the unit cost report had too much variability within itself. Because the prediction of "other structure cost" may not be of practical use, costs other than superstructure, substructure, and approach construction costs were grouped into one group called the "other" cost. The "other" cost therefore included other structure, mobilization/demobilization, traffic control, demolition, and miscellaneous costs. The miscellaneous cost item included construction engineering, training, and field office costs.

Table 2.2 shows percentage splits of the four cost components by bridge type in terms of mean, standard deviation (SD) and coefficient of variation (CV). For this cost data set, coefficients of variation seemed to be close among the four bridge types. This implied that one could obtain fairly consistent analytical results from this data set for different bridge types. The superstructure cost component accounted for about one-third of the total bridge construction cost for concrete and steel beam bridges, whereas it was

Table 2.2 Percentage Contribution to Total Bridge Cost by Four Cost Components

BRIDGE TYPE	COST GROUP: SUPERSTRUCTURE COST	SUBSTRUCTURE COST	APPROACH COST	OTHER COST
BOX BEAM & RC SLAB (n = 112)	Mean = 31.11% SD = 8.22% CV = 26.42%	Mean = 11.82% SD = 6.39% CV = 54.06%	Mean = 39.45% SD = 11.19% CV = 28.37%	Mean = 17.63% SD = 5.91% CV = 33.52%
CONCRETE I – BEAM (n = 36)	Mean = 31.10% SD = 6.84% CV = 21.99%	Mean = 16.69% SD = 6.78% CV = 40.62%	Mean = 36.84% SD = 11.27% CV = 30.59%	Mean = 15.38% SD = 4.74% CV = 30.82%
STEEL BEAM (n = 22)	Mean = 33.42% SD = 11.17% CV = 33.42%	Mean = 15.64% SD = 4.80% CV = 30.69%	Mean = 36.94% SD = 11.33% CV = 30.67%	Mean = 14.01% SD = 5.42% CV = 38.69%
STEEL GIRDER (n = 16)	Mean = 45.63% SD = 9.25% CV = 20.27%	Mean = 15.50% SD = 6.27% CV = 40.45%	Mean = 26.35% SD = 10.95% CV = 41.56%	Mean = 12.51% SD = 4.19% CV = 33.49%
ALL TYPES (n = 186)	Mean = 32.63% SD = 9.33% CV = 28.60%	Mean = 13.53% SD = 6.60% CV = 48.78%	Mean = 37.52% SD = 11.69% CV = 31.16%	Mean = 16.33% SD = 5.75% CV = 35.21%

about 45 percent for steel girder bridges. The second largest cost component was the approach construction cost and it also accounted for about one-third of the total construction cost. The remaining portion was split between the substructure cost and other cost. If three cost components (superstructure, substructure and approach costs), which account for approximately 82% to 87% of the total replacement cost, can be accurately estimated, an effective assessment can be done of bridge replacement cost allocation.

2.2.4 Study Approach

As mentioned earlier, two basic steps were followed in the cost analysis. First, an analysis of variance (ANOVA) was performed to evaluate the degree of impact of classification factors upon unit costs. Then, using the results of the analysis of variance, replacement cost prediction models were developed.

Three classification factors were used for the analysis of variance: superstructure type, substructure type, and highway type. Table 2.3 shows the levels of these three fixed factors originally considered in the analysis. Superstructure type is the main structure type as specified by FHWA's SIA guide. Four superstructure types were considered: RC slab and box-beam, concrete I-beam, steel beam, and steel girder. In this chapter, bridge types and superstructure types are used synonymously.

For substructure type, three groups were used. Bridges with hammerhead piers and solid stem piers were classified into the same group because the only difference between these two types was the cantilever portion of the hammerhead piers. Bridges with pile type piers require far less materials compared to solid stem piers. Therefore, these bridges were grouped into a

Table 2.3 Classification Factors Considered for Unit Structure Replacement Cost Analysis

Factor	Level
Superstructure Type	-Box Beam & RC Slab -Concrete I-Beam -Steel Beam -Steel Girder
Substructure Type	-With Solid Stem Piers *Hammerhead pier *Solid stem pier -With Pile Type Piers *Frame bent *Pile bent *Integral slab pier *Battered pier -Abutment Only or Arch Type (1)
Highway Type	-Interstate (1) -Primary Highway -Secondary Highway -Urban Highway (1) -Off-System

Note: (1) Only a few samples were available for analysis

separate group. The last group includes bridges which do not have piers: bridges supported solely by abutments and arch bridges.

Highway type was considered to find whether functional highway classification, such as interstate and primary highways, would affect the construction cost of superstructures. FHWA requires the state to provide separate unit costs for federal-aid system and off-system bridges.

For developing cost prediction models, multiple linear regression models were first employed. However, they were not able to meet the three basic assumptions of linear regression, that is, linearity of the regression function, normality of residuals, and constancy of variance along the regression lines. Therefore, a non-linear regression approach and a transformed linear regression analyses were performed. The aptness of regression models was first tested. As the aptness of non-linear models was not satisfied for the four cost components, transformed regression models were developed. The general model used in this analysis was an intrinsically linear model which was obtained by transforming a non-linear function into a linear function by common logarithm in order to meet the three regression assumptions of linear models.

2.2.5 Results of ANOVA on Unit Structure Costs

Unit structure costs were divided into three groups: superstructure cost, substructure cost, and total structure costs. FHWA requires states to report total unit structure costs by bridge and highway types (on- or off-system). Using three fixed factors, a two-way analysis of variance was conducted on these three unit cost groups to assess any differences among the mean unit

costs of bridges in the given factor combinations. Major objectives were to examine whether these factors would substantially affect the estimation of unit structure costs and to evaluate whether there is a definite need to compute unit costs for the highway and bridge type combinations.

2.2.5.1 Unit Superstructure Cost

As the model used for the ANOVA on unit superstructure cost had unequal cell frequencies, the MANOVA procedure of the SPSS package was used [Hull and Nie 1981]. Figure 2.2 shows the design of experiment employed and the number of samples available for this analysis. A model of four bridge (superstructure) types and five highway types was originally designed. However, it was found that only a few bridges were replaced on interstate highways and urban federal-aid highways. Therefore, these two highway types were excluded from the analysis. Among the remaining three highway types, however, bridges on off-system highways caused a significant heterogeneity of variance to this model. As shown in Figure 2.3, standard deviations of unit costs of bridges on primary and secondary highways had only small variations at different levels of mean values. However, the standard deviation of unit costs of bridges on the off-system highways showed substantial differences at various levels of mean values, causing the heterogeneity of variances for this three-level model. The existence of heterogeneous variances among the cells violates one of the basic assumptions of the analysis of variance.

It was not possible to reduce the large variance associated with off-system bridges by commonly used transformations of raw data values. Consequently, because only relatively few bridges were replaced on this highway

Superstructure Type

Highway Type		Box Beam & RC Slab	Concrete I-Beam	Steel Beam	Steel Girder
	Primary	47	23	14	10
	Secondary	72	21	7	4
	Off-System	12	6	4	3

Figure 2.2 A Two-Way ANOVA Design for Superstructure Cost Estimation

Figure 2.3 Mean vs. Standard Deviation of Unit Superstructure Costs

system, off-system bridges were excluded from the analysis and the number of levels for highway types were reduced to two, primary and secondary. The inference drawn from this analysis therefore can be applied only to these two highway types. Analyses of unit structure costs of bridges on interstate, urban federal-aid, and off-system highways should be made after an adequate number of sample data is accumulated.

The reduced ANOVA model performed was

$$C_{ijk} = \mu + H_i + S_j + HS_{ij} + \varepsilon_{(ij)k} \tag{2.1}$$

where, C_{ijk} was the unit superstructure cost, μ was the grand mean, H_i was the highway type, S_j was the bridge type, HS_{ij} was the interaction of highway type and bridge type, and $\varepsilon_{(ij)k}$ was the error term. The k subscript on the error term was included to emphasize replication of unit cost samples. Both classification factors were treated as fixed factors. With the reduced model, the Cochran's C-test statistic was 0.227 and the homogeneity of variance was accepted at $\alpha = 0.03$. Anderson and McLean [1974] stated that if the homogeneity test is accepted at $\alpha = 0.01$, there is no need to transform the data. Therefore, the analysis of variance was conducted on the raw data.

Due to the sequential sums of squares method used by the MANOVA procedure [Hull and Nie 1981], the result of ANOVA is affected by the order of introducing two main factors, bridge type and highway type, into the model. The sums of squares for each factor effect are adjusted for all effects previously entered into the model [Hull and Nie 1981]. Therefore, two runs were made, one with the bridge type as the first entry and the other with the highway

type as the first entry. The ANOVA table resulting from the reduced model is shown in Table 2.4. It was found that in both cases effects of highway type and the interaction of two factors on the mean unit costs were not significant at a 5% significance level. Therefore, with available data, it was concluded that as far as unit superstructure cost is concerned, only the bridge or superstructure type can be the major factor affecting mean cost values. Table 2.5 shows the mean unit costs, standard errors of the mean (SE), and the upper (UL) and lower (LL) limits of the 95% confidence intervals. This table illustrates that only a small difference exists between the mean unit costs and their 95% confidence intervals of the two highway types.

An analysis of covariance was then performed on the same data set in which covariates, bridge length and deck width, were used in conjunction with bridge (superstructure) type to evaluate whether these two variables may affect the result of the two-way analysis. It was found that the regression effect due to these two covariates was not significant at a 5% significance level, indicating that the two main factors, bridge and highway types, are the major factors creating differences among unit superstructure costs. This analysis showed that only the bridge (superstructure) type was significant at a 5% significance level. However, the highway type was not significant at the same significance level. Therefore, it can be said that mean unit superstructure costs are affected only by superstructure type and there is no need to compute two different unit superstructure costs for the bridges on primary and secondary highways. This result seemed to be reasonable because bridge design standards do not differ for these two highway types.

Table 2.4 Analysis of Variance for Highway Type by Superstructure Type on Unit Superstructure Costs

Source of Variation	Sum of Squares	Degrees of Freedom	Mean Square	F-Value	Significance of F
a) Enter Highway Type as the First Factor					
Within Cells (Error Term)	4554.65	190	23.97		
Constant	141,876.18	1	141,876.18	5918.45	0*
HWYTP	11.81	1	11.81	0.49	0.484**
SUPTP	2716.48	3	905.49	37.77	0*
HWYTP by SUPTP	25.49	3	8.50	0.35	0.786**
b) Enter Superstructure Type as the First Factor					
Within Cells (Error Term)	4554.65	190	23.97		
Constant	141,876.18	1	141,876.18	5918.45	0*
SUPTP	2703.20	3	901.07	37.59	0*
HWYTP	25.09	1	25.09	1.05	0.308**
SUPTP by HWYTP	25.49	3	8.50	0.35	0.786**

Cochran's C-Statistic = 0.227, Probability = 0.030 (Approx.)

NOTE: * - Significant at the 0.001 level
** - Not significant at the 0.25 level
SUPTP - Superstructure Type (Main effect)
HWYTP - Highway System Type (Main effect)
SUPTP by HWYTP - Interaction effects of highway type by Superstructure type

		Superstructure Type			
		Box Beam & RC Slab	Concrete I-Beam	Steel Beam	Steel Girder
Highway Type	Primary	N = 47 Mean = 25.62 SE = 0.71 LL = 24.23 UL = 27.01	N = 23 Mean = 23.40 SE = 1.02 LL = 21.40 UL = 25.40	N = 14 Mean = 29.90 SE = 1.31 LL = 27.33 UL = 32.47	N = 10 Mean = 37.94 SE = 1.55 LL = 34.90 UL = 40.98
	Secondary	N = 72 Mean = 25.81 SE = 0.58 LL = 24.67 UL = 26.95	N = 21 Mean = 24.81 SE = 1.07 LL = 22.71 UL = 26.91	N = 7 Mean = 31.19 SE = 1.85 LL = 27.56 UL = 34.82	N = 4 Mean = 40.58 SE = 2.45 LL = 35.78 UL = 45.38

N - Number of Samples
Mean - Mean Unit Superstructure Cost ($/square foot of deck area)
SE - Standard Error of the Mean
LL - Lower Limit of 95% Confidence Interval
UL - Upper Limit of 95% Confidence Interval

Table 2.5 Two-Way ANOVA Design for Unit Superstructure Cost Analysis with Mean, Standard Error of the Mean, and 95% Confidence Interval

When some factors are not substantially influential and their significance probability is greater than 0.25, it is allowed to pool the residual error with error terms [Anderson and McLean 1974]. Therefore, a separate one-way ANOVA was run on the combined data set of bridges on primary and secondary highways and 95% confidence intervals of mean unit costs were obtained for these four superstructure types. Mean unit superstructure costs and their 95% confidence intervals are shown in Table 2.6. The 95% confidence interval implies that ninety-five times out of one hundred, the interval obtained (between LL and UL in the table) will cover the true mean unit superstructure costs for these four bridge types. As shown in Table 2.5, the confidence interval of mean unit cost for concrete bridges was very narrow, indicating that this mean unit cost would be a good number to estimate superstructure costs. The confidence interval for steel bridges was also adequately narrow to predict superstructure construction costs of steel bridges. It should be noted that unit costs are given in 1985 dollars, and appropriate FHWA structure cost indices should be used to adjust these costs for other years.

Precisions of the mean unit costs were then computed at a 95% confidence level. The precision is the amount of deviation of the estimated mean from the true mean value [Blank 1980]. Precision values are affected by the number of samples used in the analysis. The precisions of the four bridge (superstructure) types, RC slab, concrete I-beam, steel beam, and steel girder, were \$0.85, \$1.37, \$2.48, and \$2.71 per square foot of deck area, respectively.

2.2.5.2 <u>Unit Substructure Cost</u>

Unit substructure costs are were expressed in dollars per square foot of

Superstructure Type			
Box Beam & RC Slab	Concrete I-Beam	Steel Beam	Steel Girder
N = 119 Mean = 25.73 SE = 0.45 LL = 24.85 UL = 26.61	N = 44 Mean = 24.07 SE = 0.73 LL = 22.64 UL = 25.50	N = 21 Mean = 30.33 SE = 1.06 LL = 28.25 UL = 32.41	N = 14 Mean = 38.69 SE = 1.30 LL = 36.14 UL = 41.24

N - Number of Samples
Mean - Mean Unit Superstructure Cost ($/square foot of deck area)
SE - Standard Error of the Mean
LL - Lower Limit of 95% Confidence Interval
UL - Upper Limit of 95% Confidence Interval

Table 2.6 One-Way ANOVA Design for Unit Superstructure Cost Analysis with Mean, Standard Error of the Mean, and 95% Confidence Interval

deck area and classified by highway type and superstructure type by INDOT at the time of the present study. Considering diverse factors affecting substructure constructions such as the location of the foundation and the substructure type, unit costs classified only by bridge type may be too simplistic for accurately estimating actual substructure cost. An analysis of variance was, therefore, performed on unit substructure costs using bridge (superstructure) type and substructure type as the main effects to examine whether the substructure type should be considered to compute unit substructure costs. The substructure type was selected as it was the next logical choice for factoring unit substructure costs. Effects of highway class were assumed to be small judging from the results of analyses on unit superstructure costs.

Table 2.7 shows the model considered in this analysis along with mean unit costs, standard errors of the mean, and 95% confidence intervals. Two substructure types were used, solid-stem piers and pile-type piers. The third type, bridges with only abutments or arch support, was excluded from this analysis because there were only a few samples found in this group. For practical uses, however, results from the stem-pier type can be used to estimate costs of bridges in the third group. The substructure types included in these two groups are found in Table 2.3. Since this model had unequal cell frequencies, the MANOVA procedure of the SPSS package was again used and a similar process used for analyzing unit superstructure costs was employed.

Table 2.8 shows the ANOVA table for the model considered. The Cochran's C-test statistic was 0.225 and the homogeneity test was accepted at $\alpha = 0.05$. Therefore, there was no need for data transformation. It was found that the

		Superstructure Type			
		Box Beam & RC Slab	Concrete I-Beam	Steel Beam	Steel Girder
Sub-structure Type	Solid Stem Type	N = 27 Mean = 13.60 SE = 0.98 LL = 11.68 UL = 15.52	N = 30 Mean = 14.19 SE = 0.93 LL = 12.37 UL = 16.01	N = 13 Mean = 14.29 SE = 1.41 LL = 11.53 UL = 17.05	N = 13 Mean = 12.88 SE = 1.41 LL = 10.12 UL = 15.64
	Pile Type	N = 91 Mean = 8.30 SE = 0.53 LL = 7.26 UL = 9.34	N = 7 Mean = 11.34 SE = 1.92 LL = 7.58 UL = 15.10	N = 7 Mean = 19.07 SE = 1.92 LL = 15.31 UL = 22.83	No Sample Available

N - Number of Samples
Mean - Mean Unit Substructure Cost ($/square foot of deck area)
SE - Standard Error of the Mean
LL - Lower Limit of 95% Confidence Interval
UL - Upper Limit of 95% Confidence Interval

Table 2.7. Two-Way ANOVA Design for Unit Substructure Cost Analysis with Mean, Standard Error of the Mean, and 95% Confidence Interval

Table 2.8 Analysis of Variance for Superstructure Type by Substructure Type on Unit Substructure Costs

Source of Variation	Sum of Squares	Degrees of Freedom	Mean Square	F-Value	Significance of F
a) Enter Superstructure Type as the First Factor					
Within Cells (Error Term)	4669.91	181	25.80		
Constant	23,770.58	1	23,770.58	921.32	0
SUPTP	1050.88	3	350.29	13.58	0*
SUBTP	354.38	1	354.38	13.74	0.0003*
SUPTP by SUBTP	381.55	2	190.77	7.39	0.001*
b) Enter Substructure Type as the First Factor					
Within Cells (Error Term)	4669.91	181	25.80		
Constant	23,770.58	1	23,770.58	921.32	0
SUBTP	978.01	1	978.01	37.91	0*
SUPTP	427.25	3	142.42	5.52	0.001*
SUBTP by SUPTP	381.55	2	190.77	7.39	0.001*

Cochran's, C-Statistic = 0.225, Probability = 0.124 (Approx.)

NOTE: * - Significant at the 0.05 level
SUPTP - Superstructure type (Main effect)
SUBTP - Substructure Type (Main effect)
SUPTP by SUBTP - Interaction effect of superstructure type by substructure type.

main effects as well as their interaction were significant at 5% significance level, as shown in the table. Figure 2.4 illustrates the interaction effect of superstructure type by substructure type for the model shown in Table 2.6. As shown in the figure, mean unit substructure costs of bridges with solid-stem type piers were generally higher than those with pile-type piers for the concrete bridges. Steel beam bridges, however, showed a different trend, but this difference might have been caused by site-specific reasons, because unit substructure costs of steel beam bridges with pile-type piers are usually lower than those with solid-stem piers. Due to this unexpected outcome of mean unit substructure costs, the result of this ANOVA was not conclusive to substantiate the expected trend. Nevertheless, by looking at the trend shown by concrete bridges, it can be concluded that the substructure type would affect the unit substructure cost, and that the addition of the substructure type would improve the accuracy of estimated substructure costs.

Unit substructure costs for the different superstructure and substructure combinations indicated that superstructure type had less effect on unit substructure cost for the bridges with solid-stem type piers than for the bridges with pile type piers. The differential effect of superstructure type on unit substructure costs between the two substructure types implied that the superstructure and substructure factors interact in their effect on unit substructure costs.

In order to account for factors other than bridge structure length and deck width, which can be used to compute unit substructure costs, an analysis of covariance was run on the same data set with vertical clearance and the number of spans as covariates to assess whether these variables may reduce the

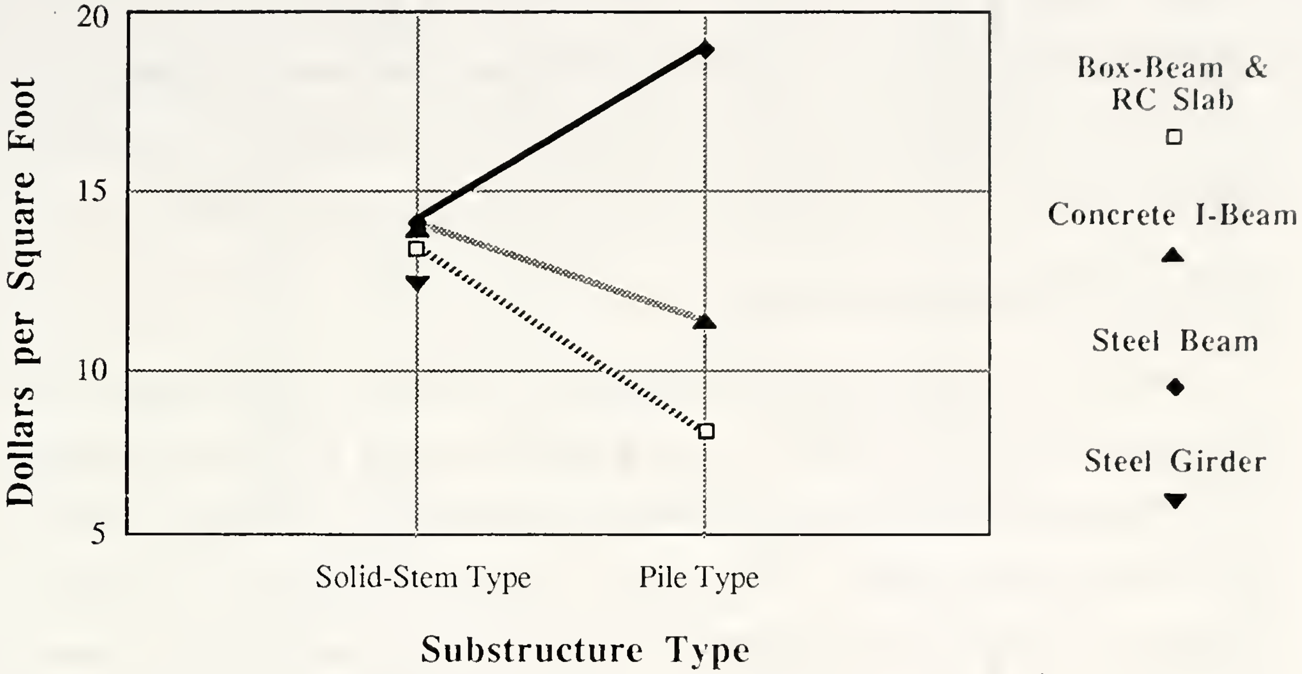


Figure 2.4 Unit Substructure Costs by Superstructure Type and by Substructure Type

interaction effect. It was found that the regression effect by these two covariates became significant at 5% significance level. After the sum of squares for the regression effect was subtracted, the two main effects and their interaction were still significant at 5% significance level. The implication of this result is that even after taking into account the effects of structure length, deck width, vertical clearance and number of spans, there still existed a significant difference among unit substructure costs which could be accounted for by the superstructure and substructure types.

2.2.5.3 Unit Total Structure Cost

Unit total structure cost is simply the sum of unit superstructure cost and unit substructure cost. In the previous section, it was discussed that the substructure type affects unit substructure costs. It was tested whether this effect still remains in unit total structure costs because the effect of substructure type might be reduced when added to unit superstructure costs. The same model used for the unit substructure cost analysis was used by replacing unit substructure costs with unit total structure costs.

Table 2.9 shows the analysis of variance model applied to unit total structure costs as well as the mean values, standard errors of the mean, and 95% confidence intervals of total unit structure costs for the main effect combinations. Table 2.10 gives the ANOVA table for the design of analysis shown in Table 2.9. The homogeneity test was accepted at $\alpha = 0.001$. Anderson and McLean [1974] suggested that if the test is accepted between $\alpha = 0.01$ and $\alpha = 0.001$, transformation is not needed unless there is a practical reason to transform. A histogram of raw data was plotted and it was found that total

		Superstructure Type			
		Box Beam & RC Slab	Concrete I-Beam	Steel Beam	Steel Girder
Sub-structure Type	Solid Stem Type	N = 27 Mean = 39.02 SE = 1.35 LL = 36.37 UL = 41.67	N = 30 Mean = 38.03 SE = 1.28 LL = 35.52 UL = 40.54	N = 13 Mean = 45.74 SE = 1.94 LL = 41.94 UL = 49.54	N = 13 Mean = 51.10 SE = 1.94 LL = 47.30 UL = 54.90
	Pile Type	N = 91 Mean = 34.11 SE = 0.73 LL = 32.68 UL = 35.54	N = 7 Mean = 37.01 SE = 2.65 LL = 31.82 UL = 42.20	N = 7 Mean = 47.88 SE = 2.65 LL = 42.69 UL = 53.07	No Sample Available

N - Number of Samples
Mean - Mean Unit Total Structure Cost ($/square foot of deck area)
SE - Standard Error of the Mean
LL - Lower Limit of 95% Confidence Interval
UL - Upper Limit of 95% Confidence Interval

Table 2.9 Two-Way ANOVA Design for Unit Total Structure Cost Analysis with Mean, Standard Error of the Mean, and 95% Confidence Interval

Table 2.10 Analysis of Variance for Superstructure Type by Substructure Type on Unit Total Structure Costs

Source of Variation	Sum of Squares	Degrees of Freedom	Mean Square	F-Value	Significance of F
a) Enter Superstructure Type as the First Factor					
Within Cells (Error Term)	8888.17	181	49.11		
Constant	272,007.30	1	272,007.30	5539.20	0
SUPTP	4577.20	3	1525.73	31.07	0*
SUBTP	312.00	1	312.00	6.35	0.013*
SUPTP by SUBTP	218.08	2	109.04	2.22	0.112**

b) Enter Substructure Type as the Second Factor

Source of Variation	Sum of Squares	Degrees of Freedom	Mean Square	F-Value	Significance of F
Within Cells (Error Term)	8888.17	181	49.11		
Constant	272,007.30	1	272,007.30	5539.20	0
SUBTP	1891.99	1	1891.99	38.53	0*
SUPTP	2997.21	3	999.07	20.35	0*
SUBTP by SUPTP	218.08	2	109.04	2.22	0.112**

Cochran's C-Statistic = 0.296, Probability = 0.001 (Approx.)

NOTE: * - Significant at the 0.05 level
** - Not significant at the 0.10 level
SUPTP - Superstructure Type (Main effect)
SUBTP - Substructure Type (Main effect)
SUPTP by SUBTP - Interaction effect of superstructure type by substructure type

unit structure cost data were normally distributed. Raw data were transformed by common logarithm to see whether the scattering of data points was normally distributed. Two histograms showed basically the same shape and therefore transformation of raw data was not required.

The interaction was dramatically reduced and it became not significant at 5% significance level ($\alpha = 0.112$ with raw data). However, two main effects were still significant at 5% significance level. From this analysis it can be said that the substructure type does affect unit total structure costs, in addition to the bridge (superstructure) type. Therefore, it will be better to compute total superstructure costs separately for the two substructure groups for achieving better estimates of replacement costs.

2.2.6 Results of ANOVA on Approach Construction Cost

Average approach construction costs of new bridges are difficult to estimate because of many factors affecting the construction of approach roads. Because of the diversity of site specific factors, approach costs are often estimated as a lump-sum value and not much analysis has been conducted on this subject. However, at the network level bridge management, the prediction of approach costs is an important element because it would account for a substantial portion of the total construction cost once approach roads are needed. In the sample data, approximately twenty-five to forty percent of total replacement costs was used to construct approach roads, as shown in Table 2.2.

The attributes of approach roads that can affect approach construction cost are approach length, approach width, and the amount of earthwork. The approach length was defined as the length of the project after the bridge

structure length is subtracted. The approach width was the summation of roadway pavement width and the shoulder width. The earthwork was the sum of common excavation, borrow, and excavation for subgrade treatment.

Histograms of approach length and earthwork were plotted and samples were grouped into three categories, each consisting approximately one-third of the entire data set. Approach length was divided into three groups, short, medium, and long approaches. Earthwork was divided into three levels, small, medium, and large. After preliminary analyses, approach width was excluded from further consideration because there was not much variation in the approach width of the sample data, and its effect was found to be insignificant in the analysis. Table 2.11 shows the ANOVA model used for this analysis. Although the cells did not have an equal sample size, each row and column had approximately one-third of the entire sample. The ranges of the three groupings are also shown in the figure for reference.

Since the model had unequal cell frequencies, the MANOVA procedure was again used. The homogeneity test was rejected at $\alpha = 0.001$ for raw data and the transformation was made by using common logarithm ($\log_{10}$). With the transformed data, the Cochran's C-statistic was 0.208 and the homogeneity of variance was accepted at $\alpha = 0.05$. The ANOVA model performed on approach construction costs was:

$$\text{Log}_{10} A_{ijk} = \mu + L_i + E_j + LE_{ij} + \varepsilon_{(ij)k} \tag{2.2}$$

where, A_{ijk} was the actual approach construction cost, μ was the grand mean, L_i was the approach length, E_j was the amount of earthwork, LE_{ij} was the

Approach Length	Amount of Earthwork: Small	Medium	Large
Short	N = 47 Mean = 80.1 LL = 70.1 UL = 91.6	N = 15 Mean = 121.1 LL = 95.5 UL = 153.7	N = 3 Mean = 179.8 LL = 105.5 UL = 306.2
Medium	N = 13 Mean = 121.0 LL = 93.7 UL = 156.2	N = 40 Mean = 158.4 LL = 136.9 UL = 183.3	N = 21 Mean = 268.9 LL = 219.9 UL = 328.9
Long	No Sample Available	N = 7 Mean = 257.8 LL = 181.9 UL = 365.4	N = 46 Mean = 330.7 LL = 288.7 UL = 378.8

N - Number of Samples
Mean - Mean Approach Construction Cost (in $1000)
LL - Lower Limit of 95% Confidence Interval
UL - Upper Limit of 95% Confidence Interval

Ranges of Factor Values

* Approach Length		* Approach Earthwork	
Short:	0 ft. < L < 500 ft.	Small:	0 cys < E < 2,000 cys
Medium:	500 ft. < L < 1,000 ft.	Medium:	2,000 cys < E < 8,000 cys
Long:	1,000 ft. < L < 5,280 ft.	Large:	8,000 cys < E < 50,000 cys

Table 2.11 Two-Way ANOVA Design for Approach Cost Analysis with Mean and 95% Confidence Interval

interaction of approach length by amount of earthwork, and $\varepsilon_{(ij)k}$ was the error term. Two main factors were treated as fixed effects. Table 2.12 shows the ANOVA table of this model. It was found that the interaction of two factors was not significant at all (P-value = 0.614). Two main effects were, however, significant at a 5% significance level. This implied that two factors, approach length and approach earthwork, can be used as grouping factors for estimating approach construction costs.

Table 2.11 shows 95% confidence intervals of the cell means. The measurement unit of cost is 1,000 dollars in this table. For instance, one can be 95% sure that the interval obtained will cover the true mean approach construction costs for these ranges of approach length and earthwork, as shown in the table. It can be seen that the cells along the diagonal provided best estimates. Cells with a small sample size had wider confidence intervals. Although the grouping used in the analysis was somewhat broad, results appeared to be promising for making initial rough estimates of approach construction costs.

2.2.7 Summary of ANOVA on Bridge Replacement Costs

The previous two sections discussed results of statistical analyses on costs of bridge superstructure, substructure, and approach construction, that can be used to make initial cost estimates. Unit structure costs are often used to estimate total structure costs. FHWA requires states to submit total unit structure costs by highway type and by bridge (superstructure) type. The replacement cost analysis tested whether this classification could be adequate to account for variations in unit costs caused by site specific factors of

Table 2.12 Analysis of Variance for Approach Length and Amount of Earthwork on Approach Construction Costs

Source of Variation	Sum of Squares	Degrees of Freedom	Mean Square	F-Value	Significance of F
a) Enter Approach Length as the First Factor					
Within Cells (Error Term)	7.698	184	0.0418		
Constant	946.677	1	946.677	22,626.59	0
LENGTH	8.705	2	4.353	104.03	0*
EARTH	1.773	2	0.887	21.19	0*
LENGTH by EARTH	0.0076	3	0.025	0.60	0.614**
b) Enter Earthwork as the First Factor					
Within Cells (Error Term)	7.698	184	0.0418		
Constant	946.677	1	946.677	22,626.59	0
EARTH	9.435	2	4.717	112.75	0*
LENGTH	1.044	2	0.521	12.47	0*
EARTH by LENGTH	0.076	3	0.025	0.60	0.614**

Cochran's C-Statistic = 0.208, Probability = 0.110 (Approx.)

NOTE: * - Significant at the 0.001 level
** - Not significant at the 0.25 level
LENGTH - Approach Length (Main effect)
EARTH - Amount of Earthwork (Main effect)
LENGTH by EARTH - Interaction effect of approach length by the amount of earthwork

bridge construction.

As for superstructure construction costs, the analysis was conducted only for primary and secondary highway types. The difference in the mean unit costs for these two highway types was not statistically significant. Adequate samples were not available for other highway types, that is, interstate, urban highway, and off-system.

Currently, the substructure type is not used to compute unit substructure and total structure costs. However, it was found in this analysis that substructure type affects unit substructure and unit total structure costs. In this analysis, costs were considered in terms of two substructure types: substructure with solid stem piers and pile piers. This simple two-type grouping considerably improved the precision of making estimates of substructure construction costs.

The results suggest that unit structure costs for bridge replacement can be calculated for a combination of superstructure and substructure types. For substructure types, solid-stem and pile type piers are recommended for unit cost calculations.

To analyze approach construction costs, total costs instead of unit costs were used since too many factors would be needed to compute such unit costs. The analysis conducted on approach construction costs showed that the prediction of approach costs could be improved by categorizing such costs in terms of approach length and amount of earth work. Both approach length and amount of earth work were subdivided using broad groupings. For instance, the mean approach cost for a short approach with a small amount of earth work was

$80,000 and its confidence interval was $20,000. As the approach road becomes longer and earth work becomes larger, the confidence interval increases indicating that there was more variation in such larger approach constructions. For a long approach and large earth work, the mean construction cost was $330,000, whereas the confidence interval was $116,700.

The analysis emphasized the application of statistical principles to assess the accuracy of unit bridge costs for using them as a means to estimate future bridge construction costs. Often, average values are used as representative costs, but unless the deviation of costs are known, one is not sure about the precision of average values. Standard errors of the mean and 95% confidence intervals of the mean unit costs should help engineers and inspectors understand how much variability might be expected when average values are used.

2.2.8 Development of Cost Prediction Models

Predictive regression models were developed for estimating bridge replacement costs. Actual contract costs were used in developing the prediction models. The independent variables in these models are those which engineers and inspectors can easily understand.

2.2.8.1 General Form of Prediction Models

Results of the analyses of variance and scatter plots of dependent variables using the SPSS package [13] showed that models of the following type could be applied:

$$Y = \beta_0(X_1^{\beta_1} \ldots X_n^{\beta_n})\varepsilon \tag{2.3}$$

where, Y is the replacement cost, β_i is a regression coefficient, X_i is an independent variable, and ε is the error term.

This model results in a curve which is often used by economists when studying the relation between the price of a commodity (X) and the quantity demanded (Y) at that price [Neter and Wasserman 1974]. This relationship was found to be appropriate for application in estimating bridge construction costs. There are two ways to perform regression analyses on data of this type. One analysis is to apply a non-linear regression analysis. If two regression assumptions are met (the constancy of variance of regression residuals and the normality of residual distribution), one can use the results of a non-linear regression analysis. Otherwise, one should consider transforming raw data.

The non-linear model shown in Equation 2.3 had to be transformed so that the parameters appeared in a linear fashion. A logarithmic transformation was used:

$$Y' = \beta_0' + \beta_1 X_1' + \ldots + \beta_2 X_n' + \varepsilon' \tag{2.4}$$

where, $Y' = \log_{10}(Y)$, $\beta_0' = \log_{10}(\beta_0)$, $X_i' = \log_{10}(X_i)$ and $\varepsilon' = \log_{10}(\varepsilon)$.

If this transformed model met the regression assumptions, it could be brought back to the following non-linear form:

$$Y = \text{antilog}(\hat{\beta}_0)X_1^{\hat{\beta}_1} \ldots X_n^{\hat{\beta}_n} \tag{2.5}$$

The multiple linear regression analysis procedure of the SAS statistical package was used because this package provides convenient options for residual analyses to check the assumption required for regression models [SAS 1985].

2.2.8.2 Comparison of Non-Linear and Intrinsically Linear Models

A comparative analysis was performed to assess the aptness of non-linear regression models and transformed linear regression models. Table 2.13 shows results of this comparison. The assumptions required for regression analyses were tested (the normality of residual distribution and the constancy of variance along the regression lines). The reduction of the error sum of squares was also used to test which method would account for more variation.

As shown in Table 2.13, the non-linear regression functions on raw data of the four cost components did not meet the two assumptions discussed above. Residual plots were obtained to check the constancy of variance and the Kolomogorov-Smirnov test was administered to check the normality of the distribution of residuals. For non-linear models, the variance of residuals had a tendency to increase as the predicted cost increased. For transformed linear models, however, variance along the regression functions seemed to be constant. Figure 2.5 demonstrates this difference using the superstructure cost as an example.

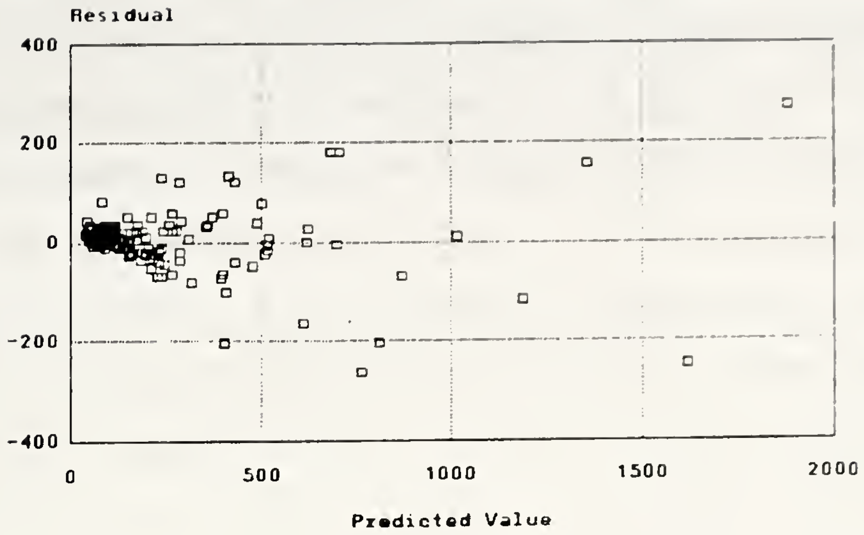
Table 2.13 also gives the significance probabilities for the models

Table 2.13 Comparison of Non-Linear and Transformed Intrinsically Linear Regression Models

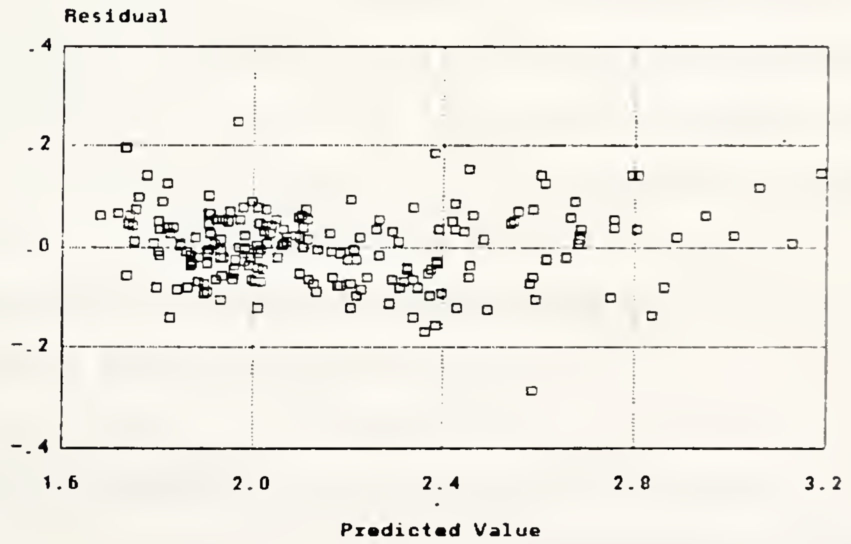
Component	Type	Cost Prediction Model	# of Samples	Linearity R^2 & F-Ratio	Residual Analysis: Normality check by Kolomogorov D-Statistic at $\alpha = 0.05$	Residual Analysis: Constancy of Variance	Residual Analysis: SSE	Residual Analysis: δ SSE* (Reduction of SSE)
Bridge Total	Transformed	$BRTC = 0.155\ BL^{0.903} DW^{0.96}$	186	$R^2 = 0.823$ $F = 423.95$	Prob = 0.06 Normal	Yes	5,911,997	548,597 (9.2%)
	Non-linear	$BRTC = 0.263\ BL^{0.955}\ DW^{0.767}$		-	Prob = <0.01 Not Normal	No	5,363,400	
Superstructure	Transformed	$SUPC = 0.0107\ BL^{1.122}\ DW^{1.084}$	196	$R^2 = 0.725$ $F = 168.35$	Prob = >0.15 Normal	Yes	959,690	341,488 (35.6%)
	Non-linear	$SUPC = 0.00336\ BL^{1.252} DW^{1.205}$		-	Prob = <0.01 Not Normal	No	618,202	
Substructure	Transformed	$SUBC = 0.00168\ BL^{0.906}\ DW^{1.255}\ VC^{0.487}$	196	$R^2 = 0.725$ $F = 168.25$	Prob = 0.12 Normal	Yes	775,550	80,115 (10.3%)
	Non-linear	$SUBC = 0.00698\ BL^{0.897}\ DW^{0.909}\ VC^{0.514}$		-	Prob = <.01 Not Normal	No	695,435	
Other Miscellaneous	Transformed	$OTHC = 0.0721\ BL^{0.696}\ DW^{0.932}$	186	$R^2 = 0.524$ $F = 100.60$	Prob = >0.15 Normal	Yes	362,064	27,533 (7.6%)
	Non-linear	$OTHCC = 0.114\ BL^{0.772}\ DW^{0.736}$		-	Prob = <0.01 Not Normal	No	334,531	
Approach	Transformed	$APC = 4.715\ APL^{0.403}\ EW^{0.250}$	192	$R^2 = 0.696$ $F = 215.93$	Prob = <0.01 (1) Not Normal	Yes	2,638,087	323,491 (12.3%)
	Non-linear	$APC = 1.952\ APL^{0.509}\ EW^{0.299}$		-	Prob = <0.01 (2) Not Normal	No	2,314,596	

NOTE: * (SSE of the transformed model - SSE of the non-linear model)
(1) Kurtosis = 0.855
(2) Kurtosis = 5.893

DEFINITIONS: BL = Bridge Structure length in feet
APL = Approach length in feet
VC = Vertical clearance in feet
DW = Bridge deck (out-to-out) width in feet
EW = Amount of earthwork in 100 cys.



(a) Residual Plot for Non-Linear Regression Function



(b) Residual Plot for Transformed Linear Regression Function

Figure 2.5 Comparison of Residual Plots of the Non-Linear Regression Function and Transformed Linear Regression Function

tested. The normality test resulted in a significant difference between the theoretical and actual distribution of residuals for non-linear models. The residual distributions of all transformed intrinsically linear models, except for the approach construction model, were found to be normal at 5% significance level.

For approach construction cost models, kurtosis of residual distribution was computed for comparison, since both models were found to be not normal at the one percent significance level. Kurtosis is a measure that indicates the peakedness of a distribution. In the SAS output, the value of kurtosis for a normally distributed population is zero [SAS 1985]. The kurtosis of the transformed model was 0.855 and the kurtosis of the non-linear model was 5.893, as given in Table 2.13. Since both values were positive, these two residual distributions are more peaked than a normal distribution. The residual distribution of the non-linear model was, however, found to be far more peaked than that of the transformed model. Therefore, the transformed model was considered to be superior to the non-linear model.

As for the reduction of error sums of squares, non-linear models were more efficient than transformed linear models, as shown in Table 2.13. However, since non-linear models did not meet the two requirements, transformed intrinsically linear models were chosen for developing replacement cost prediction models for this study.

2.2.8.3 <u>Superstructure Cost Models</u>

At first, three factors were considered: structure length, out-to-out bridge deck width, and the degree of the skew of superstructure. It was found

that the skew was not a significant factor for the bridges in the data set. Although the influence of deck width after entering the bridge length variable in the equation was small, it was retained for two reasons. First, its inclusion did improve the models. Second, it is natural for bridge engineers and inspectors to make cost estimates using bridge length and bridge width. Table 2.14 lists the regression functions obtained for superstructure costs. As shown in the table, coefficients of determination (R^2) of these regression functions were very high. Eighty-seven to ninety-seven percent of cost variations were accounted for by regression models for the four superstructure types. These models were studied for their appropriateness. Residual plots were used to check the constancy of variance requirement. The normality check of residuals was performed by the Kolomogorov-Smirnov test of goodness-of-fit [SAS 1985]. It was found that the linearized models met the three basic requirements of linear regression, that is, linearity, constancy of variance, and normality of residuals. In the regression functions, costs are expressed in thousands of dollars and structure length and deck width are entered into the models in feet. It should be noted that the equations presented in Table 2.14 are applicable only within the ranges of span, deck width and vertical clearance included in the data set.

2.2.8.4 Substructure Cost Models

In the unit substructure cost analysis, it was found that the substructure type, in addition to the superstructure type, affects substructure unit costs. It would have been ideal to develop models for the two factor combinations. However, because of the limited number of samples for each treatment combination, it was not practical to develop prediction models for all

Table 2.14 Superstructure and Substructure Cost Prediction Models (in 1985 Dollars)

Component	Type	Regression Equation	R^2	F-Ratio	Sample Size
Superstructure	All Types	$SUPC = 0.0107\ (BL)^{1.122}\ (DW)^{1.084}$	0.951	1,861.28	196
	RC-Slab & Box Beam	$SUPC = 0.0137\ (BL)^{1.001}\ (DW)^{1.161}$	0.874	380.74	113
	Concrete I-Beam	$SUPC = 0.0330\ (BL)^{0.907}\ (DW)^{1.043}$	0.913	205.34	42
	Steel Beam	$SUPC = 0.0102\ (BL)^{1.120}\ (DW)^{1.117}$	0.971	317.50	22
	Steel Girder	$SUPC = 0.0885\ (BL)^{0.906}\ (DW)^{0.747}$	0.950	150.91	19
Substructure	All Types	$SUBC = 0.00168\ (BL)^{0.906}\ (DW)^{1.255}\ (VC)^{0.487}$	0.725	168.35	196
	Solid Stem Type*	$SUBC = 0.00506\ (BL)^{0.744}\ (DW)^{1.205}\ (VC)^{0.515}$	0.751	143.62	196
	Pile Type*	$SUBC = 0.00354\ (BL)^{0.744}\ (DW)^{1.205}\ (VC)^{0.515}$			

* An indicator variable was used for developing substructure cost models.

NOTATIONS: SUPC = Superstructure cost in 1,000 dollars
SUBC = Substructure cost in 1,000 dollars
BL = Bridge structure length in feet
DW = Deck width (out-to-out) in feet
VC = Vertical clearance in feet

possible combinations of superstructure and substructure types. It was found that for solid-stem type substructures, unit substructure costs were similar to each other regardless of superstructure types. For pile-type substructures, however, this was not exactly true, due mainly to the inadequate number of samples. Therefore, only the substructure type was used as a grouping factor to reflect a difference between the unit costs for solid-stem piers and pile type piers. Regression models were developed for the two substructure types combined as well as separately for each substructure type. For developing substructure cost prediction models for each type, an indicator variable was used. Since the degree of freedom of the regression with indicator variables decreases only by the number of indicator variables, the overall accuracy of the resulting models would be similar to the model with the two substructure types combined.

Since non-linear regression functions did not meet the two requirements of aptness tests, the common logarithm was used for transformation. The transformed model met the three basic assumptions of linear regression: linearity, constancy of variance, and normal distribution of regression residuals. The general form of the substructure cost prediction model follows:

$$\mathrm{Log}_{10}(\mathrm{SUBC}) = \beta_0' + \beta_1' * \mathrm{Log}_{10}(\mathrm{BL})$$

$$+ \beta_2' * \mathrm{Log}_{10}(\mathrm{DW}) + \beta_3' * \mathrm{Log}_{10}(\mathrm{VC}) + \beta_4' * \mathrm{T} \qquad (2.6)$$

where,

SUBC = Substructure cost in \$1,000,

BL = Bridge structure length in feet,

DW = Out-to-out deck width in feet,

VC = Vertical clearance in feet, and

T = Indicator variable

(1 if solid stem pier, 0 if pile type pier).

The solid stem type included hammerhead and solid stem piers, whereas the pile type included frame bent, pile bent, integral slab, and battered piers. The coefficient of indicator variable was significant at the one percent significance level, implying that the substructure type substantially affects predicted substructure costs. The parameters for the three independent variables entered were also significant at the one percent significance level. Solid-stem piers would cost approximately 40% more than pile type piers. Substructure cost prediction models obtained from this analysis are found in Table 2.14. This table shows non-linear forms which were transformed back from intrinsic linear regression forms obtained from the analysis.

2.2.8.5 Approach Cost Models

During the unit approach cost analysis, two factors, approach length and amount of earthwork, were found to be significant in affecting approach construction costs. Regression models were therefore developed using these two types. First, cost prediction models were developed for three levels of earthwork, small, medium, and large, with approach length as a predictor variable. Another model was then developed for all levels of earthwork together. Table 2.15 lists the regression models developed for each case. It was found that the regression relation exists in each case; however, the overall model was found to provide a better predictive power than the three separate models.

Table 2.15 Approach Cost Prediction Models (in 1985 Dollars)

Group	Regression Model*	R^2	F	Sample Size
All levels of Earthwork	$APC = 0.769\ (APL)^{0.823}$	0.566	248.08	192
	$APC = 39.876\ (EW)^{0.378}$	0.633	328.20	
	$APC = 4.715\ (APL)^{0.403}\ (EW)^{0.250}$	0.696	215.93	
Small Earthwork	$APC = 4.426\ (APL)^{0.418}\ (EW)^{0.259}$	0.345	15.02	60
Medium Earthwork	$APC = 1.549\ (APL)^{0.553}\ (EW)^{0.281}$	0.320	13.88	62
Large Earthwork	$APC = 8.273\ (APL)^{0.558}\ (EW)^{0.306}$	0.477	30.54	70

* All regression models were significant at $\alpha = 0.05$.

NOTATIONS: APC = Approach cost in 1,000 dollars
APL = Approach length in feet
EW = Earthwork in 100 cubic yards
Earthwork is the summation of common excavation, excavation for subgrade treatment, and borrow.

As shown in Table 2.15, results of regression analysis seem to be quite promising for estimating approach costs related to replacing or constructing new bridges. It should be noted that bridges which had no approach road length were considered outside the population of interest for this study and excluded from the analysis. The models shown in Table 2.15 become less accurate as the value of independent variable approaches zero. Approach costs are expressed in thousands of dollars. The approach length is entered in feet, and the amount of earthwork is entered in hundreds of cubic yards.

2.2.8.6 "Other" Cost and Total Bridge Cost Models

Like the above three-component models, a common logarithm was employed to transform raw data to develop prediction models for the "other" cost and total bridge cost, since the non-linear regression analysis did not meet the two basic assumptions. Table 2.16 gives the resulting regression functions for the "other" cost and the total bridge replacement cost. No distinction was made for the bridge superstructure type to analyze these costs, since the reduction of samples with that variability would simply decrease the accuracy of the models. The coefficient of determination of the "other" cost was 0.524, which was reasonably good for this type of observational data. The coefficient of determination of the total bridge cost was 0.823, which was very good considering the fact that the approach construction cost and the "other" cost showed a wide variation among the data.

2.2.9 Validation of the Models

The replacement cost models developed in this study were validated using costs of bridges replaced between January and June, 1986. At the time of data

Table 2.16 "Other" and Bridge Total Cost Prediction Models (in 1985 Dollars)

Component	Type	Regression Equation	R^2	F-Ratio	Sample Size
Other	All Types	$OTHC = 0.0721\ (BL)^{0.696}\ (DW)^{0.932}$	0.524	100.60	186
Bridge Total	All Types	$BRTC = 0.155\ (BL)^{0.903}\ (DW)^{0.964}$	0.823	423.95	186
	RC-Slab & Box Beam	$BRTC = 0.0781\ (BL)^{0.748}\ (DW)^{1.319}$	0.549	66.46	112
	Concrete I-Beam	$BRTC = 1.255\ (BL)^{0.809}\ (DW)^{0.534}$	0.732	44.95	36
	Steel Beam	$BRTC = 0.128\ (BL)^{0.785}\ (DW)^{1.210}$	0.731	25.75	22
	Steel Girder	$BRTC = 0.353\ (BL)^{1.015}\ (DW)^{0.603}$	0.866	41.91	16

NOTATIONS: OTHC = Other cost in 1,000 dollars
BRTC = Bridge total cost in 1,000 dollars
BL = Bridge structure length in feet
DW = Deck width (out-to-out) in feet

collection for the model validation, only a fraction of the state bridges had been analyzed to compute unit superstructure and substructure costs. Therefore, several county bridges were included to have an adequate number of samples for comparison. In total, thirty-seven (37) bridges were available for validation. Twenty-six (26) bridges had the complete information necessary to validate component models for superstructure, substructure, approach, and "other" costs. The other eleven bridges had only total cost information. The costs were compared in terms of 1986 dollars and model-predicted costs were converted to the 1986 price by using the FHWA construction price indices [Hull and Nie 1981].

First, predicted and contract total bridge costs were compared. Total bridge costs were computed by two methods. One method was to use the total bridge cost model, called an aggregate model. The other method was to sum the four component costs to determine total bridge costs and it was named a component model. In the latter case, appropriate models were chosen to estimate replacement costs. For instance, models were chosen using superstructure and substructure types as grouping factors. Results are shown in Figure 2.6, in which the diagonal line shows the 100 percent correlation of actual and predicted values. It appears that the component model predicts total bridge costs somewhat better than the aggregate model. The latter had a tendency to give higher predicted values than actual costs in the lower range. It is therefore recommended that the component model be used to predict bridge replacement costs, especially in relatively small to medium size bridge replacement projects, for example, up to $1,000,000.

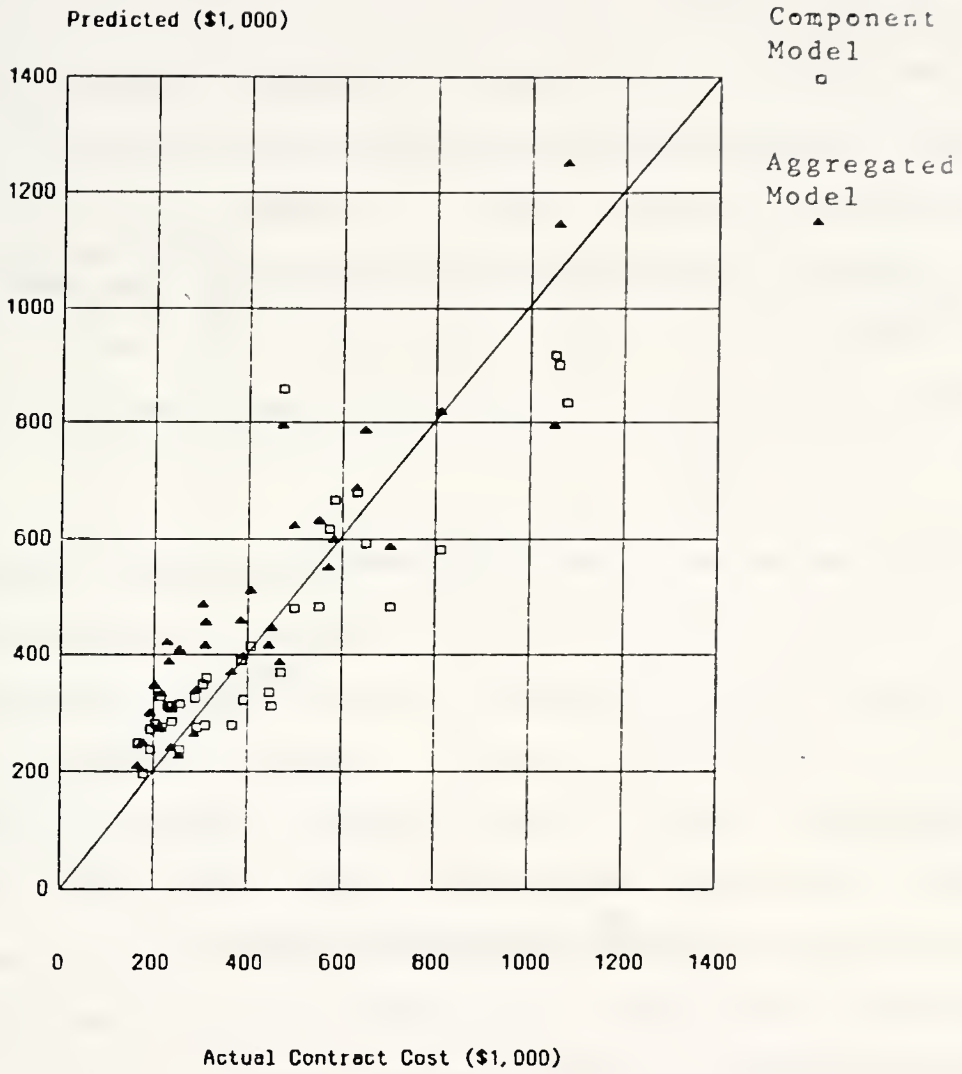


Figure 2.6 Comparison of Predicted and Actual Total Bridge Costs (in 1986 Dollars)

In a similar fashion, the four separate component models were validated. Figure 2.7 gives a comparison of actual and predicted superstructure costs. As shown in the figure, the superstructure cost model can very closely predict superstructure costs.

The substructure cost models also appeared to be fairly accurate. They tended to give higher costs than the actual contract costs for the given validation data set, as given in Figure 2.8. Although there were two extremely low estimates, they were caused by an exceptionally large amount of substructure costs required for their constructions. They can be considered as outliers in a statistical analysis. This tendency was also reflected in the plot of "other" costs.

The remaining two component costs were also validated using scatter plots of actual and predicted values. Data points for the overall approach cost model were scattered widely along the diagonal line of equality. However, this was not surprising because of a relatively low value of the coefficient of determination obtained in the analysis. Variability of data points increased as the cost increased. This result indicates that a larger departure from actual costs can be expected when approach construction costs become large. The scatter plots for "other" costs also showed a similar trend, although the degree of variability was much less.

2.2.10 Application of Cost Prediction Models

Bridge replacement cost models were developed in order to incorporate them in a bridge management system so that present and future funding needs for bridge replacement can be determined. The models can be readily used by

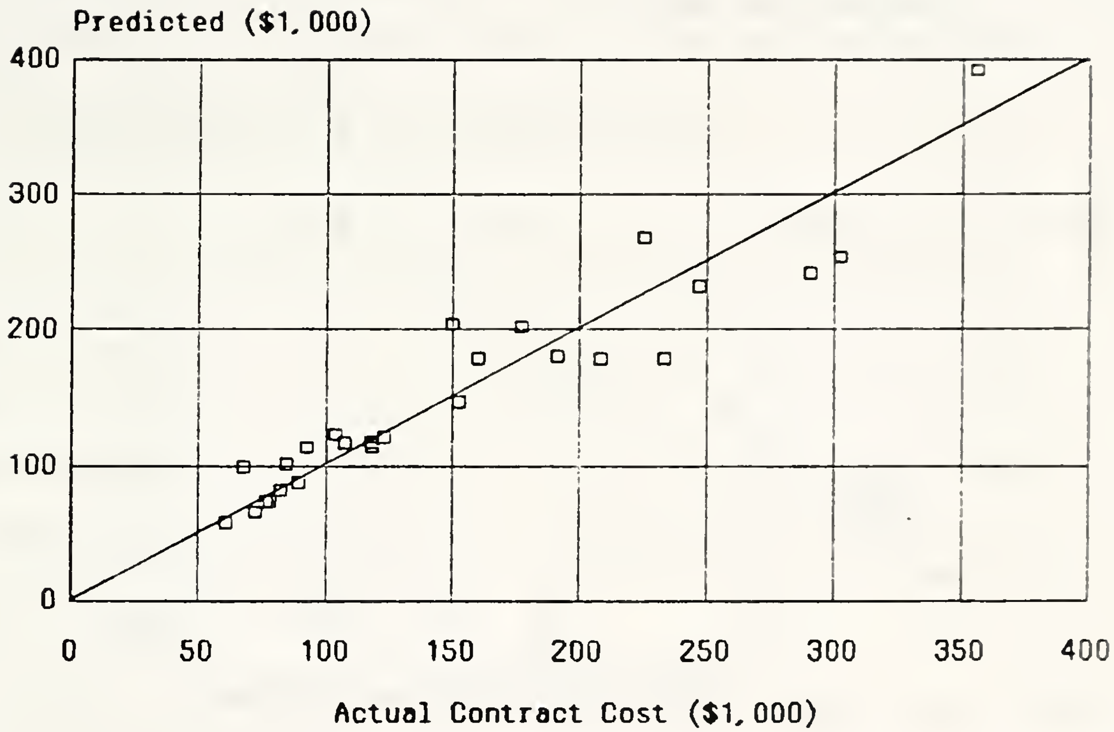


Figure 2.7 Comparison of Actual and Predicted Superstructure Costs (in 1986 Dollars)

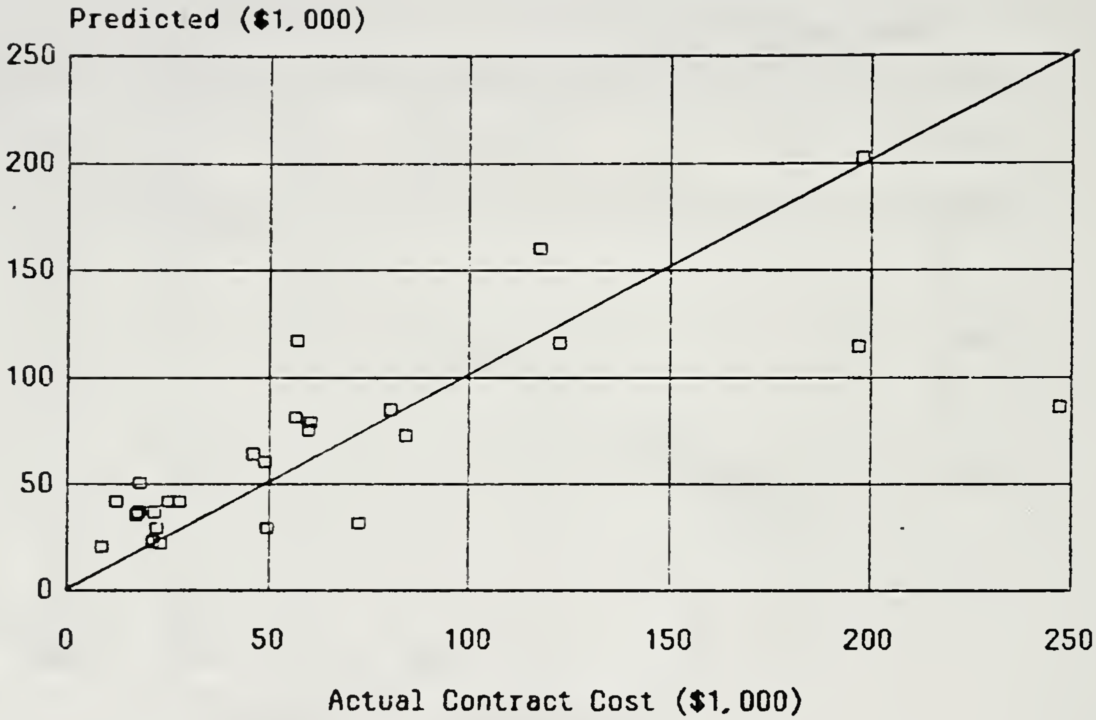


Figure 2.8 Comparison of Actual and Predicted Substructure Costs (in 1986 Dollars)

bridge engineers and inspectors through nomographs. Sample nomographs are presented in Figure 2.9 and Figure 2.10 for the superstructure cost of RC-slab bridges and for the substructure cost with an adjustment curve for various vertical clearance values, respectively. For computing substructure costs, the substructure cost determined from Figure 2.10-(a) is multiplied by the adjustment factor for vertical clearance obtained from Figure 2.10-(b). It should be noted that costs computed by these nomographs are given in the 1985 price.

2.2.11 Summary of Replacement Cost Prediction Models

As discussed in the previous sections, bridge replacement cost models developed in this study can improve the precision of future replacement cost estimates. Cost models were developed not only for the structural portion of a bridge but also for its approach and the other remaining costs included in contract cost reports. The only portions of the replacement cost which were not covered by this modeling effort were expenditures for purchasing the right-of-way and for designing bridges.

Compared to the current practice, which uses only average values without due consideration of variations among replacement costs, the new models would allow bridge managers to make more precise estimates of replacement costs required in the future. Cost models were developed using the 1985 price.

Two objectives identified at the beginning of the cost study were met by the replacement cost models. First, they can be transformed into nomographs which can be readily used by bridge managers and inspectors. Second, they can be incorporated into a bridge management system as their validity was tested

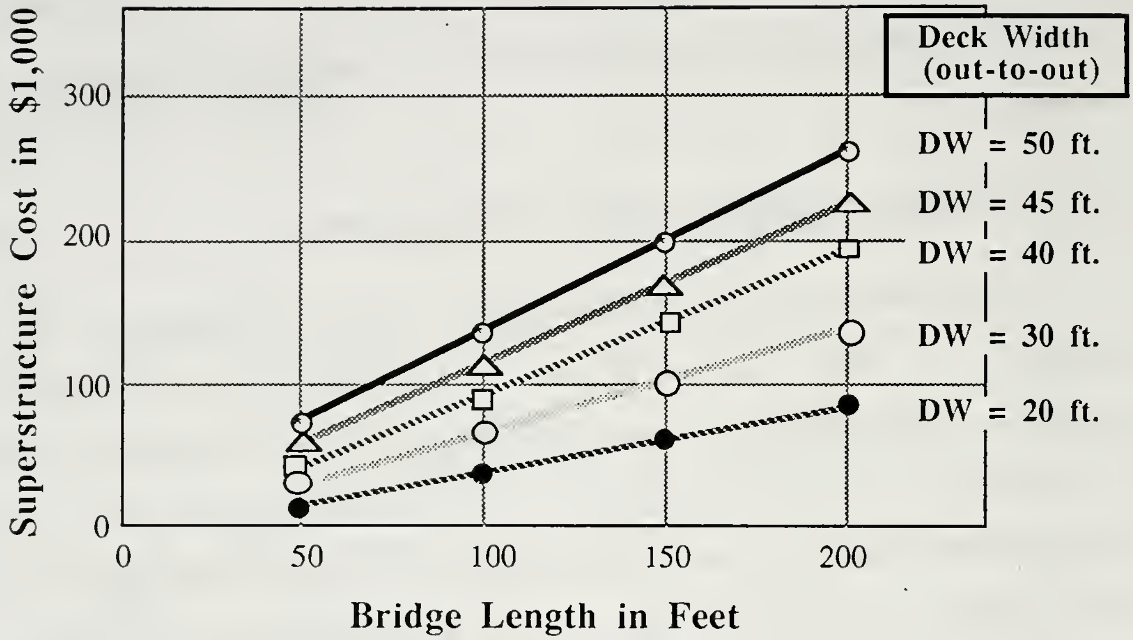
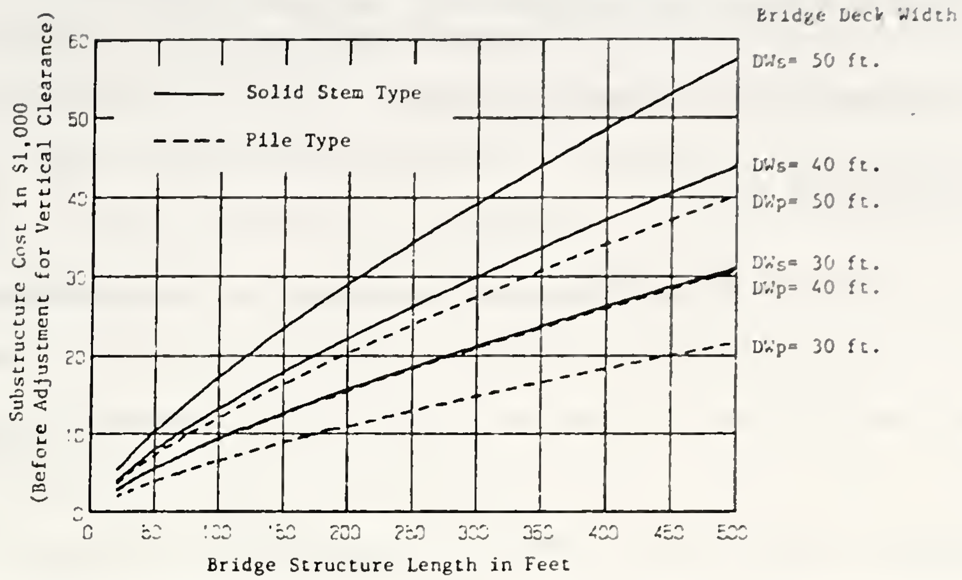
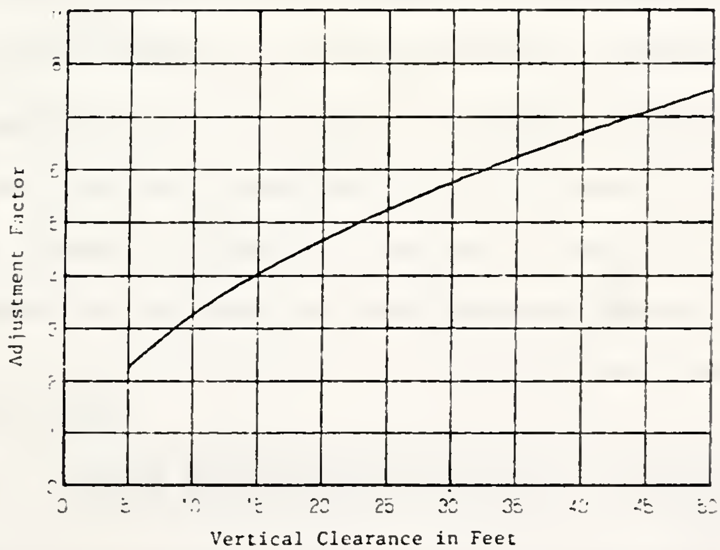


Figure 2.9 Predicted Superstructure Cost for RC-Slab and Box-Beam Bridges



(a) Substructure Before Adjustment for Vertical Clearance (in $1,000)



(b) Adjustment Factor for Vertical Clearance

Figure 2.10 Nomographs for Determining Substructure Cost

positively. Variation of costs along the regression functions can be reflected by introducing randomness into the cost models.

2.3 Bridge Rehabilitation Cost Analysis

2.3.1 Background

By correctly understanding cost and timing of rehabilitation alternatives, life-cycle cost analysis of bridges can be performed. The number of bridge rehabilitation alternatives is large as compared with pavement rehabilitation alternatives. Therefore, grouping of rehabilitation activities into a manageable number of alternatives is necessary for achieving a practical bridge management program. The FHWA SIA recording and coding guide [FHWA 1979] allows coding of four rehabilitation related activities: widening, strengthing, rehabilitation, and other structure work. For a state-level bridge management, however, these groupings are too broad and they need to be divided into more specific groups which would enable the bridge managers to make realistic cost estimates of bridge improvement programs. An investigation of bridge rehabilitation alternatives was made for Indiana, and statistical analyses were performed on two major rehabilitation activities: deck reconstruction and deck replacement.

2.3.2 Factors Considered in Estimating Rehabilitation Costs

Classification factors are helpful to group bridges so that analyses can be done for a group of bridges which have relatively homogeneous characteristics. By conducting factor analyses, one can be able to investigate what types of factors are most influential on unit costs. There can be many fac-

tors that bridge managers may wish to consider in estimating future rehabilitation expenditures. There should be, however, a trade-off between the number of factors desired and the level of detail needed for bridge management. In other words, the number of factors depends on how much aggregation managers can permit for a network level bridge management system. Four classification factors were considered in this study, as shown in Table 2.17 and discussed below.

2.3.2.1 Highway System

According to the SIA coding guide [FHWA 1979], state-owned bridges in Indiana are grouped into eight (8) types of highway system. Majority of these bridges belong to interstate, primary, and secondary highways. Highway system classification may affect the preference of bridge managers for allocating bridge funds. Often bridges on or over interstates receive more attention due to their high traffic volumes. At present, it is recommended that two highway system groups be used; interstate (INT) and other state highways (OSH). These groupings are closely related to the general distribution of truck traffic volume on highways, as discussed in the following section.

2.3.2.2 Traffic Volume

Figure 2.11 gives the distributions of average daily traffic on the eight highway systems. Majority of the bridges on interstates carry more than 5,000 ADT (Figure 2.11-a). Almost all bridges on primary and secondary rural highways carry less than 5,000 ADT (Figure 2.11-b and 2.11-c). Most bridges on urban highways carry ADT between 5,000 and 20,000 ADT(Figure 2.11-b and 2.11-d). Average daily traffic alone, however, may not be a good variable for

Table 2.17 Classification Factors for Rehabilitation Alternative Analysis

A. Highway System

1. Interstate (INT)

2. Other State Highways (OSH)

B. Traffic Volume (ADT)

1. Low Average Daily Traffic (ADT < 5,000)

2. Medium Average Daily Traffic (5,000 < ADT < 10,000)

3. High Average Daily Traffic (10,000 < ADT)

C. Climatic Region

1. Northern Region

2. Southern Region

D. Bridge Type

1. Concrete Bridges (may include prestressed concrete bridges and arch bridges)

2. Steel Bridges (may include truss bridges)

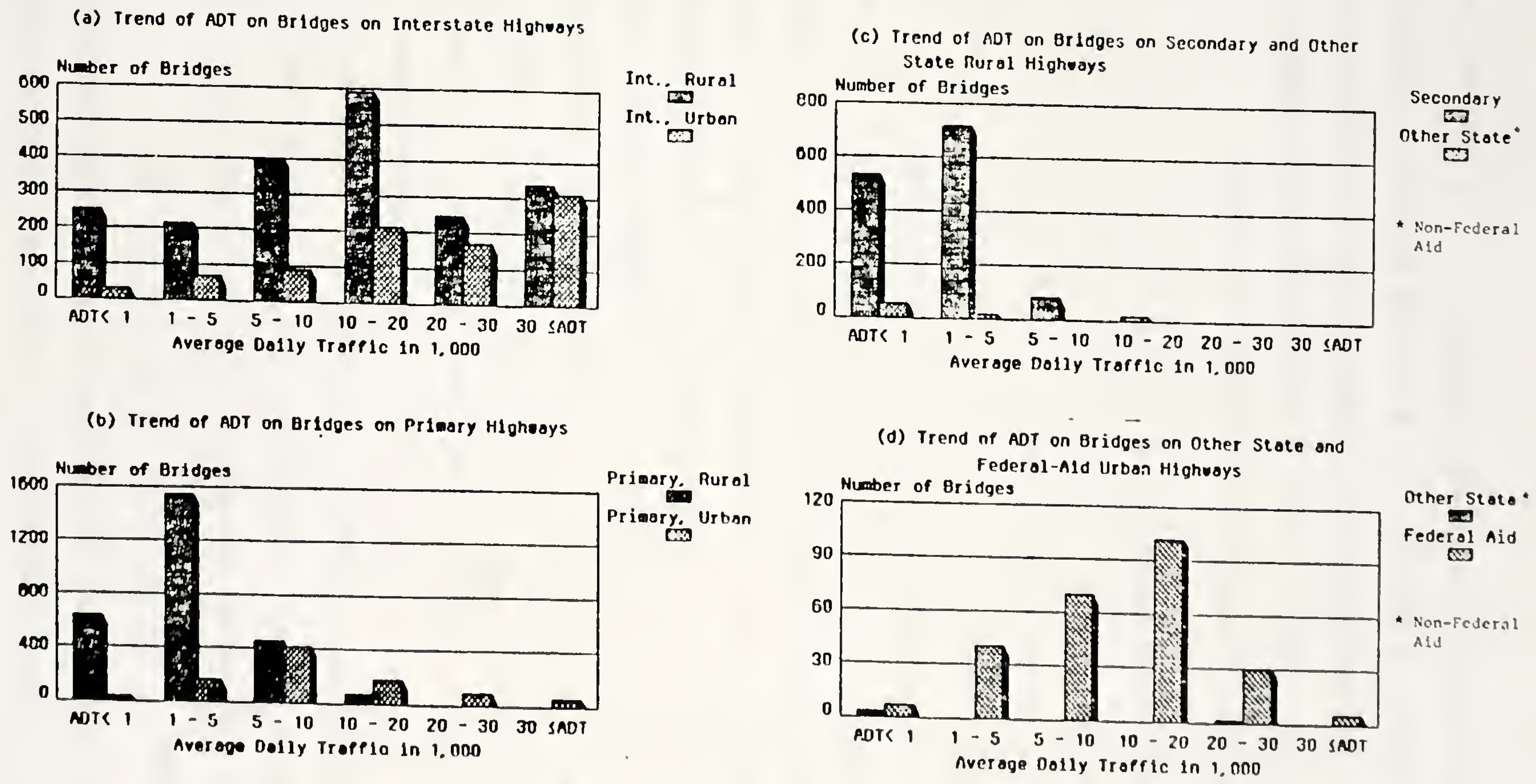


Figure 2.11 Distribution of Average Daily Traffic by Highway System

predicting bridge rehabilitation and maintenance cost or bridge performance unless truck traffic is accounted for along with ADT. Table 2.18 shows a summary of percent trucks on six of the eight highway types. Data were collected by manual counts [IDOH 1979-84]. Percentages shown in the table are average values computed from data collected between 1979 and 1984.

The average percentage of trucks is the highest on rural interstates (33%). As the average daily traffic for rural interstates are also very high, bridges on rural interstates are subject to the highest number of truck traffic. Urban interstates have a fairly low percentage of trucks (17%) as compared to rural interstates. However, since the average daily traffic on urban interstates is very high, actual truck counts can still be considered to be high. Interstates, therefore, can be grouped as a "high" truck traffic highway. Bridges on primary and secondary rural highways have similar percentages of trucks, 16% and 11% respectively. They also experience similar distributions of relatively low ADTs. These two highway systems therefore carry similar amount of truck traffic, and actual truck counts are relatively low as compared to interstates. On the other hand, the average percentage of trucks on federal-aid urban highways is the lowest (6.8%) among the highway systems considered. However, since many routes in this highway category carry high ADT, as shown in Figure 2.11-d, the actual number of trucks may be as high as secondary rural highways. Comparing with interstates, other state highway systems carry less number of trucks and they can be grouped as a "low" truck traffic highway.

By using this general distribution of truck traffic, one can combine the two levels of highway classification, interstate and other state highway, with

Table 2.18 Summary of Percent Trucks by Highway System

Highway System	Average %Trucks	Standard Deviation	Number of Stations	95% Confidence Interval		Coefficient of Variation
				Lower Limit	Upper Limit	
Interstate Rural	33.23	5.24	20	30.78	35.68	16%
Interstate Urban	17.23	6.94	21	14.07	20.39	40%
Primary Rural	15.87	7.30	46	13.71	18.04	46%
Primary Urban	14.30	6.88	10	9.37	19.23	48%
Secondary Rural	11.30	4.75	12	8.28	14.32	42%
Urban	6.80	2.89	4	2.21	11.39	42%

Remark: In this classification count study, "truck" included all vehicles other than cars, motorcycles, and light trucks (such as pickups and minivans).

the two general truck traffic levels, high and low. As discussed earlier, one can use ADT as a proxy for truck traffic levels within each highway system type. As the relationship between the truck traffic level and the severity of distresses is not clear, it is considered to be adequate to have only aggregated groupings, such as high, medium, and low ADTs.

2.3.2.3 Climatic Region

Climatic conditions significantly affect performance of various bridge components, particularly bridge deck. Deicing chemicals have been found to cause rapid deterioration of concrete decks. In order to account for the effect of climate, two climatic regions, north and south, were considered, as defined in the Indiana Cost Allocation Study [Sinha et al. 1984].

2.3.2.4 Bridge Type

About 97% of the state-owned bridges are of conventional types. Consequently, only the conventional bridges were included in the study and bridges of exceptional structures such as suspension bridges and cable-stayed bridges were excluded. Two bridge types were considered in the rehabilitation cost analysis: concrete and steel bridges.

2.3.3 INDOT Definition of Rehabilitation Work

The district bridge inspector together with the district engineer and maintenance supervisors determine which bridges should be recommended for major repair work, or rehabilitation, and for minor maintenance work, based upon the results of the latest field bridge inspections. Rehabilitation activities are those which are judged to require consultation of the Bridge

Design Section of the Central Office. They are contract works which go through the Program Development Division, Design Division, and Construction Section of INDOT. All bridge rehabilitation projects are given contract numbers unique to them. Table 2.19 gives a list of rehabilitation activities performed during the three year period of 1984-86. It can be seen that approximately 80% of the activities fell under the deck reconstruction and overlay alternative. Minor repair works, such as deck patching and erosion protection of small sizes, are performed by INDOT maintenance forces at districts and subdistricts. Routine maintenance tasks such as deck cleaning and deck flushing are also done by INDOT maintenance forces. There is no other system of performing bridge repair works within INDOT. There is a possibility of letting emergency repairs and other small repairs at the district level. However, this has been discouraged by the Central Office and these contracts have rarely taken place in the past several years.

2.3.4 Problems Associated with Coding Rehabilitation Alternatives

The FHWA SIA Guide [FHWA 1979] requires the state to record the type of work proposed to be accomplished on the bridge to improve it to the point that it will provide the type of service specified for certain bridges. Out of the eight improvement types listed in Item 75 of the Guide [FHWA 1979], four are related to rehabilitation according to the definition of bridge rehabilitation used in the INDOT Biennial Highway Improvement Programs. They are (a) widening existing bridge or other major structure, (b) rehabilitation, (c) strengthening, and (d) other structure work. Although these groupings may be satisfactory for a nation-wide bridge inventory, they are too broad for a

Table 2.19 Bridge Rehabilitation Categories Used by INDOT in a Three Year Period and Their Minimum and Maximum Unit Costs (Dollars per Square Foot of Deck Area): 1984-1986

Rehabilitation Alternative	Number of Bridges	Unit Cost	
		Minimum	Maximum
1. Deck Reconstruction & Overlay	360	1.37	32.28
2. Deck Reconstruction	6	6.49	30.58
3. New Deck & Widening	7	6.81	36.28
4. New Deck	8	14.68	63.21
5. New Superstructure, etc.	5	19.29	65.31
6. Deck Reconstruction & Widening	17	13.93	69.49
7. Superstructure Reconstruction & Widening	2	24.73	-
8. Major Reconstruction	2	27.57	-
9. Deck Replacement & Widening	4	11.07	72.70
10. Concrete Arch Rehabilitation	1	9.76	-
11. Portals & Chords Repair	1	15.16	-
12. Concrete Arch Abutment Repair	1	19.29	-
13. Superstructure Replacement	3	23.18	35.23
14. Replace Beams	2	3.97	25.68
15. Deck Widening	1	31.34	-
16. New Deck & Abutment Repair	1	63.21	-
17. Repair Members	1	2.16	-
18. Shoulder Reconstruction	1	2.16	-
19. Repair Beams	1	4.24	-
20. Add Floor Beams	1	4.36	-
21. New Deck Reconstruction	1	9.05	-
22. Arch Reconstruction	1	13.22	-
23. Deck Replacement	2	20.52	30.19
24. Arch Widening	1	71.33	-
25. Deck Reconstruction & Joint Replacement	10	3.18	3.28
26. Superstructure Replacement & Widening	1	49.15	-
27. Reconstruction & Rail Replacement	1	2.06	-
28. Joint Reconstruction	1	6.91	-
Total	443		

Note: - In case of a single project, the unit cost was placed in the minimum unit cost column.

- Unit costs of 1984, 1985, and 1986 were listed without any adjustments.

state-level bridge management. For example, widening may comprise of two types. One type of widening is associated with deck replacement. The other type of widening requires simply the addition of partial deck with an overlay over the entire deck. Unit costs and service lives of these two activities may substantially differ. It is necessary for the INDOT to consider an appropriate set of bridge rehabilitation alternatives. In order to provide guidance to the development of bridge rehabilitation groupings, a list of rehabilitation activities was prepared using the information from literature [Weyer and McClure 1983; AASHTO 1980] and opinions of the INDOT bridge inspectors, as shown in Table 2.20. The list also includes possible maintenance options. Some of the rehabilitation activities may fall under the category of maintenance depending upon the magnitude of required tasks. It should be noted that the activities can be singular or in combination.

2.3.5 Problems Associated with Current Rehabilitation Alternative Groupings

The records of approximately 440 bridges rehabilitated in 1984, 1985, and 1986, were examined. Most of the activities included deck and superstructure work. Substructure rehabilitation accounted for only a small portion of the total bridge rehabilitation cost and there were only a few types of substructure rehabilitation works. These included the repointing of masonry substructures, addition of rivetment ripraps, dumping of gabions to protect substructure from erosion, encasement of substructure foundations, and repair of erosion control slopes near the abutments. Current rehabilitation groupings are often inconsistent. Consequently, the task of estimating rehabilitation costs is a difficult one. Maximum and minimum unit costs, expressed as dollars per

Table 2.20 A Suggested List of Rehabilitation and Maintenance Activities

A. Bridge Deck

1. Replace the entire deck
2. Replace part of the deck
3. Resurface bridge deck
4. Major widening in addition to replacing the entire deck
5. Minor widening in conjunction with deck overlaying
6. Deck patching including full depth patching
7. Repair curbs, median, sidewalk, and parapet
8. Repair or replace expansion joints
9. Repair or replace railings
10. Repair or replace drainage
11. Deck cleaning

B. Superstructure

a. Steel Superstructure

1. Replace the entire superstructure
2. Repair or replace main structural members (beams, floor beams, girders)
3. Repair or replace secondary structural members (stringers, diaghrams)
4. Widen superstructure
5. Tighten or replace bolts
6. Repair or replace defective welds or rivets
7. Strengthen truss members
8. Strengthen truss floor beams or stringers
9. Paint structural members
10. Repair, reset, or replace bearings and bearing seats
11. Clean lower chords or truss or bearing areas
12. Miscellaneous repairs

b. Concrete Superstructure

1. Repair or patch concrete beams, arch ring, diaphragms
2. Replace concrete beams
3. Repair or replace bearing devices
4. Widen superstructure

Table 2.20 (continued)

C. Substructure

a. Piers, Abutments, and Wing Walls

1. Patch deteriorated concrete bridge seats, piers, abutments, and wing walls
2. Repair or replace concrete or timber wing walls
3. Add or replace of erosion control fixtures
4. Repoint or dri-pack masonry
5. Add supportive abutments and wing walls to the existing abutments and wing walls.
6. Repair or replace timber pile caps
7. Repair or replace timber piles (includes concrete encasement)
8. Repair or replace timber backwall (includes concrete encasement)
9. Repair or replace steel substructure

b. Foundation Protection

1. Add temporary support to abutments or piers
2. Encase footings or piles
3. Correct erosion problems
4. Correct stream scour problems
5. Clean out channel

square foot of deck area, recorded in the past three years, are shown in Table 2.19. The values in the table illustrate the degree of variation existing among the unit costs of activities currently recorded as rehabilitation. Unit costs of projects included under the same rehabilitation alternative may vary substantially. Some of the problems associated with the bridge rehabilitation cost analysis based on the data available at the INDOT are illustrated by considering two rehabilitation categories, deck reconstruction and new deck and widening.

2.3.5.1 <u>Deck Reconstruction</u> & <u>Overlay</u>

The deck reconstruction and overlay is the most often used rehabilitation alternative and the one which is often wrongly classified. By definition, this term indicates reconstruction of the deck by shallow and/or full-depth patching of deteriorated spots and an overlay of the deck after scarifying the wearing surface. Along with this reconstruction, curbs, railing, and expansion joints are replaced in most cases. Other related works include guardrails, approach slab reconstruction, approach shoulder reconstruction, and small amounts of substructure repairs. However, many projects recorded under this category actually had a deck replacement instead of deck reconstruction. Also, in one case, the damaged part of a steel beam was straightened, thus resulting in a superstructure rehabilitation. For concrete arch bridges, spandrel walls may have been reconstructed as well as the deck itself. Depending upon the extra work involved or misclassification of rehabilitation activities, unit costs indicated a wide range, from \$1.91 to 30.02 in 1984, from \$4.48 to \$32.28 in 1985, and from \$1.37 to \$23.89, in 1986.

2.3.5.2 New Deck and Widening

The term new deck has been loosely used. It may mean a replacement of the entire deck or a partial replacement of the deck. There were seven bridges listed under this category, six in 1984 and one in 1985. The six bridges rehabilitated in 1984 required a replacement of the entire deck and should have been listed under deck replacement and widening. Furthermore, superstructure and substructure were often modified to support the widened portion of the deck. For example, on an arch bridge, widening involved the deck only. However, on a beam bridge additional beams and pile piers were added. Depending on the extent of work done to superstructure and substructure, unit costs varied ranging from \$6.81 to \$26.30 for the arch bridges and \$36.38 for the only steel beam bridge. The bridge rehabilitated in 1985 under this category was a concrete arch bridge and it actually received an arch reconstruction work. Part of arch rings were removed and replaced as well as the deck over them. Most of the existing arch ring remained. Other works included installation of expansion joints and replacement of concrete railing with steel railing, arch ring patching, and repointing of piers and abutments. Due to the relatively small amount of work needed, the unit cost of this arch reconstruction was \$14.82.

Problems illustrated by these examples suggest that computing only one grand mean unit cost of all rehabilitation options, as done at present to report to the FHWA, may not be appropriate for a state-level bridge management. For instance, there is a substantial difference between unit costs for deck reconstruction and deck replacement. Also, one unit cost is now computed for one contract which may involve either only one or several bridges, and it

is difficult to trace the expenditures for individual bridges from the recorded data. More disaggregate information is necessary to improve the reliability of unit rehabilitation cost data.

2.3.6 Analysis of Deck Reconstruction and Overlay Alternative

2.3.6.1 Data Base

Out of 360 bridges receiving deck reconstruction and overlay during the three-year period, eighty-four met the condition of one bridge per one contract and the definition of deck reconstruction and overlay. Under this rehabilitation category, part of the deck is repaired by shallow and/or full-depth patching and the surface overlaid. For unit cost analyses, only these eighty-four bridges were used. For the remaining analyses, bridges receiving the first deck reconstruction and overlay work since construction, were used. There were 237 bridges which met this criterion. Unit costs in different years were adjusted to the 1985 price by using the FHWA construction price indices [BOC 1986]. Unit costs are expressed in dollars per square foot of deck area. These unit costs were derived from costs categorized under the bridge item cost category involving materials directly used for the repair of bridge components. All other costs, such as traffic maintenance and mobilization costs, were included in the "other" cost group.

2.3.6.2 Effects of Factors on Unit Costs

In order to examine which classification factors affect unit costs most, one-way analysis of variance was used. It was found that as far as the deck

reconstruction and overlay alternative is concerned, there was not much difference in the work done between steel and concrete bridges; most of the bridges in Indiana have reinforced concrete deck. Therefore, bridge type factor was not used in subsequent analyses.

As the model used for the ANOVA on unit costs had unequal cell sizes, the MANOVA (multivariate analysis of variance) procedure of the SPSS package [Hull and Nie 1981] was used. Table 2.21 gives the models and results of one-way (or one-factor) analysis for climatic region, highway type, and traffic volume factors. The table also shows means, standard errors of the mean, 95% confidence intervals, and significance levels. The 95% confidence interval implies that ninety-five times out of one hundred, the interval obtained (between LL and UL in the table) will cover the true mean unit costs [Neter and Wesserman 1974]. Homogeneity of variances among the factor combinations must be accepted with the significance level equal or greater than 0.001 before proceeding with the analysis [Anderson and McLean 1974]. All the three models (regional effect, highway type effect, and traffic volume effect) met the homogeneity test necessary for the assumption of the analysis of variance, as shown in the table. It was found that as far as the unit cost of the deck reconstruction and overlay alternative is concerned, effects of these three classification factors were not significant at a 95% confidence level (α = 0.05). It should be noted, however, that this result does not suggest the exclusion of the three factors from all other analyses.

After the classification factors were found not significant with respect to the unit cost, other variables, which can be readily identified by inspectors, were considered for analysis. Structure length, deck area, and percent

Table 2.21 Results of One-Way ANOVA on Unit Costs of the Deck Reconstruction and Overlay Alternative

(a) Region

North	South
N = 43 Mean = 10.64 SE = 0.71 LL = 9.22 UL = 12.06	N = 41 Mean = 10.65 SE = 0.72 LL = 9.22 UL = 12.08

Homogeneity Test Significance Level = 0.437 > 0.001
Significance Level = 0.989 > 0.05

(b) Highway System

Interstate	Other State Highway
N = 15 Mean = 10.00 SE = 1.20 LL = 7.61 UL = 12.39	N = 69 Mean = 10.79 SE = 0.56 LL = 9.67 UL = 11.91

Homogeneity Test Significance Level = 0.318 > 0.001
Significance Level = 0.554

(c) Traffic Volume in ADT

ADT < 5,000	5,000 < ADT < 10,000	10,000 < ADT
N = 44 Mean = 10.71 SE = 0.70 LL = 9.31 UL = 12.11	N = 24 Mean = 11.16 SE = 0.95 LL = 9.27 UL = 13.05	N = 16 Mean = 9.70 SE = 1.16 LL = 6.67 UL = 12.73

Homogeneity Test Significance Level = 0.579 > 0.001
Significance Level = 0.618 > 0.05

Definitions:

N = Number of samples in the cell
Mean = Mean unit cost in $ per square foot of deck area
SE = Standard error of the mean
LL = Lower limit of the 95% confidence interval of the mean
UL = Upper limit of the 95% confidence interval of the mean

of deck area needing patching were chosen for further analyses. The percent of deck area needing patching was obtained by dividing the sum total of shallow patching and full depth patching by the deck area. In this analysis, factor level boundaries were set so that each level had about one-third of the data. Table 2.22 shows the results of the analysis of variance for the three parameters. As shown in the table, length and deck area were significant at $\alpha = 0.05$ and 0.10, respectively. This result is consistent with the general belief that the unit cost tends to decrease as the bridge size increases. By using different unit costs according to the size of the deck area, better estimates of costs of deck reconstruction and overlay can be provided.

One-way ANOVA on the percent of deck area needing patching indicated that the effect of this variable was not significant at $\alpha = 0.05$. Two-way ANOVAs were then performed for the combination of deck area and percent of deck area needing patching and the combination of bridge length and percent of deck area needing patching. It was found that the former model would provide more distinct unit costs among the factor combinations than the latter model. Table 2.23 shows results of the two-way ANOVA performed on the combination of total deck area and percent of deck area needing patching. After several runs, it was found that boundary values of 500 sys (square yards) and 2,000 sys were most appropriate to get distinct unit costs. Many bridges fell between these two boundaries. Splitting this medium range into two levels, however, did not significantly change the mean unit costs. Rounded numbers were used in the analysis as boundary points for easy comprehension and implementation. Due to the sequential sums of squares method used by the MANOVA procedure, the result of ANOVA is affected by the order of introducing two

Table 2.22 Results of One-Way ANOVA on Unit Costs of Deck Reconstruction and Overlay Using Length, Deck Area and Percent of Deck Area Needing Patching as Factors

(a) Bridge Length

L < 150 ft.	150 ft. < L < 250 ft.	250 ft. < L
N = 25 Mean = 12.62 SE = 0.87 LL = 10.89 UL = 14.35	N = 37 Mean = 10.72 SE = 0.72 LL = 9.29 UL = 12.15	N = 22 Mean = 8.27 SE = 0.93 LL = 6.42 UL = 10.12

Homogeneity Test Significance Level = 0.024 > 0.001
Significance Level = 0.004 < 0.05

(b) Deck Area

DA < 800 sys	800 sys < DA < 1,500 sys	1,500 sys < DA
N = 33 Mean = 11.76 SE = 0.79 LL = 10.19 UL = 13.33	N = 33 Mean = 10.62 SE = 0.79 LL = 9.06 UL = 12.19	N = 18 Mean = 8.65 SE = 1.06 LL = 6.54 UL = 10.76

Homogeneity Test Significance Level = 0.078 > 0.001
Significance Level = 0.069 < 0.10

(c) Percent of Deck Area Needing Patching

PA < 10%	10% < PA < 20%	20% < PA
N = 32 Mean = 10.05 SE = 0.82 LL = 8.42 UL = 11.68	N = 28 Mean = 10.05 SE = 0.87 LL = 8.32 UL = 11.78	N = 24 Mean = 11.61 SE = 0.94 LL = 9.74 UL = 13.48

Homogeneity Test Significance Level = 0.058 > 0.001
Significance Level = 0.450 > 0.05

Definitions:

N = Number of samples in the cell
Mean = Mean unit cost in $ per square foot of deck area
SE = Standard error of the mean
LL = Lower limit of the 95% confidence interval of the mean
UL = Upper limit of the 95% confidence interval of the mean

Table 2.23 Effects of Deck Area and Percent of Deck Area Needing Patching on Unit Costs of the Deck Reconstruction and Overlay

		Deck Area (DA)		
		Small DA < 500	Medium 500 ≤ DA < 2,000	Large 2,000 ≤ DA
Percent of Deck Area Needing Patching (PA)	Low PA < 15%	N = 6 Mean = 13.74 LL = 9.78 UL = 19.30	N = 37 Mean = 9.09 LL = 7.94 UL = 10.40	N = 6 Mean = 5.73 LL = 4.65 UL = 7.01
	High PA ≥ 15%	N = 6 Mean = 16.09 LL = 11.45 UL = 22.60	N = 26 Mean = 10.11 LL = 8.60 UL = 11.88	N = 3 Mean = 8.11 LL = 5.02 UL = 13.12

* Homogeneity Test Significance Level = 0.009 > 0.001 (considered to be homogeneous)

Definitions:

DA = Deck area in square yards
PA = Percentage of deck area needing patching (%)
N = Number of samples
Mean = Mean unit cost (approximate values because the data were transformed by common logarithm) in $ per square foot of deck area
UL = Upper limit of the 95% confidence interval of the mean
LL = Lower limit of the 95% confidence interval of the mean

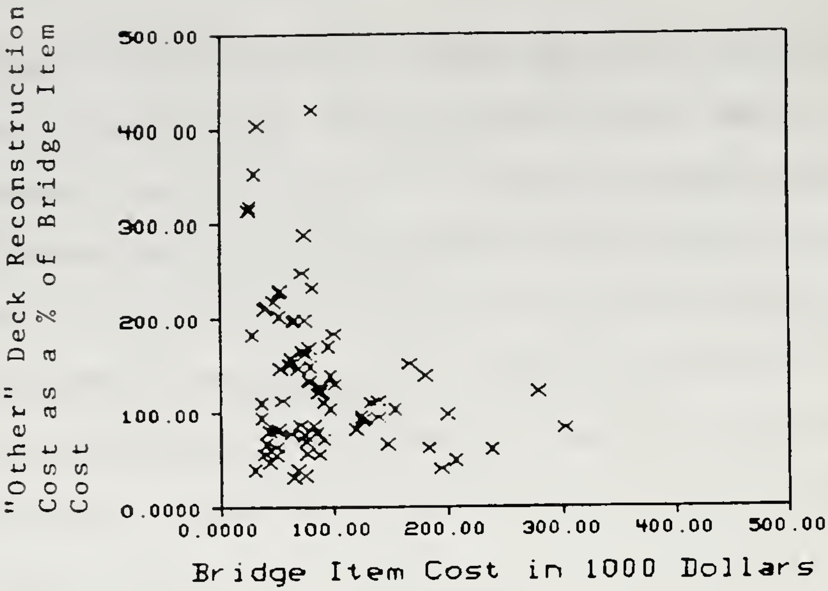
main factors and the interaction term into the model [Hull and Nie 1981]. Therefore, several runs were made by changing the order of entry of the two main factors and the interaction term. Significance of the percent patching area was dependent on the order of entry into the model. The deck area was significant at $\alpha = 0.05$ regardless of the order of entry. The percent of deck area needing patching was not significant at $\alpha = 0.05$ when it was introduced to the model after the deck area. However, when it was introduced into the model before the deck area, its significance level became 0.069. The interaction effect of the deck area and the percent patching area was not significant regardless of the order of entry at $\alpha = 0.05$. As the interaction effect was not significant, factor level means for each factor can be compared separately [Hull and Nie 1981]. The analysis result indicates that unit costs are dependent on the size of deck area and the amount of percent of deck area needing patching. Unit costs stratified by these two factors are more precise than a single mean unit cost for estimating future deck reconstruction and overlay costs.

2.3.6.3 <u>Other Deck Reconstruction Costs</u>

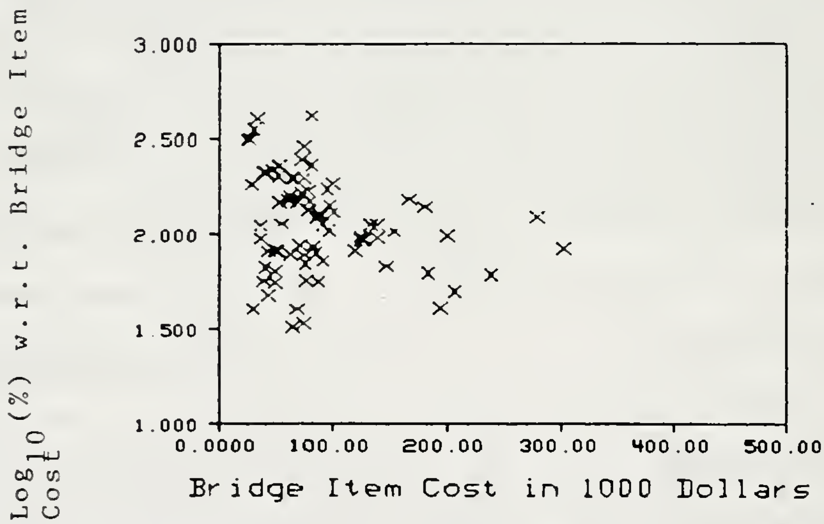
The preceding deck reconstruction cost analysis involved only the cost directly related to the bridge structure. The contract price, however, includes costs besides the bridge item cost, such as traffic maintenance and mobilization of equipment to the construction site. It was found that these additional cost items vary significantly within each cost category depending on the project. Consequently, separate analyses of these costs may not be useful for a network-level future expenditure estimation. Therefore, these costs were grouped as other deck reconstruction cost. Because bridge item

costs can be fairly accurately estimated, the other cost was expressed as a percentage of the total bridge item cost. Factors used for analyzing their effects on unit bridge item costs, such as deck area and highway type, were found not to have significant effects upon other deck reconstruction costs. The amount of other cost seems to be affected more by physical features of the construction site than the network level management factors. Hence, it would be better to consider the amount of other deck reconstruction cost as a random occurrence for a network-level bridge cost estimation.

In order to evaluate the distribution of data points, "other" reconstruction costs were plotted against total bridge item costs. Figure 2.12-(a) shows the result of this plot. The figure shows that a large variation exists among other costs at low bridge item costs as compared to high bridge item costs. Therefore, an analysis of variance (ANOVA) was performed by separating bridge item total costs into two levels: low (< \$100,000) and high (> \$100,000). Raw data had to be transformed by common logarithm ($\log_{10}$) to meet the homogeneity of variance requirement. When transformed, data points were spread with less skewness, as shown in Figure 2.12-(b). This figure, however, still shows a difference in data variations among the two cost levels. Table 2.24-(a) shows the ANOVA table. The resulted significance level of the cost level grouping effect was 0.064 and not significant at 5% significance level. Table 2.24-(b) shows the mean and its 95% confidence interval of the two cost levels. There is a large difference between the mean values (123.31% and 93.11%), and their 95% confidence intervals overlap only slightly. However, a large variance within each group most probably cancel out the effect of the two cost level groupings. Also, as shown in Table 2.24-(a), most of the sum



(a) Before transformation



(b) After transformation by Log_{10}

Figure 2.12 "Other" Deck Reconstruction Cost as a Percentage of the Bridge Item Cost vs. the Bridge Item Cost of Deck Reconstruction

Table 2.24 Results of One-Way ANOVA on "Other" Deck Reconstruction Cost

(a) ANOVA Table

Source of Variation	Sum of Squares	Degree of Freedom	Mean Squares	F-value	Significance of F
Within Cells	4.824	77	0.063		
Constant	335.150	1	335.150	5349.16	0.000
Cost Level	0.222	1	0.222	3.54	0.064

Homogeneity Test:

Cochran's C-statistic = 0.001, Probability = 0.001 (Approx.) $< \alpha = 0.001$

(b) Mean and 95% Confidence Interval of Mean

Bridge Item Cost Level ($1000)	Count	Mean** (%)	Min.** (%)	Max.** (%)	95%CI* (%)
< 100	59	123.31	32.51	420.17	108.89 to 139.64
> 100	20	93.11	40.81	183.73	75.16 to 115.35

* Converted from the transformed values

** Actual values

of squares are taken by the constant itself.

Therefore, it was felt justifiable that for a network level management, the use of the overall mean and its 95% confidence interval would still be practical and realistic. Descriptive statistics of the entire data set were therefore obtained, as shown in Table 2.25. Data were transformed by common logarithm ($\log_{10}$) to meet the normality of data distribution. As shown in Table 2.25-(a), when data are transformed, the normality of this data sample was accepted with the Kolomogorov significance probability of 0.15, which is greater than the significance level test of 0.05. The results of transformed values were converted back to their original values and shown in Table 2.25-(b). The approximate mean value of the "other" deck reconstruction cost was 114.75% of the bridge item cost associated with deck reconstruction, and its 95% confidence interval was between 100.69% and 130.91%.

2.3.7 Analysis of Deck Replacement Alternative

The deck replacement alternative is a more extensive rehabilitation work than deck reconstruction. Deck replacement consists of a replacement of the entire deck, including rehabilitation of parts of the superstructure and the top portion of the substructure. It was difficult to find a project which included only deck replacement. Several projects combined deck replacement with deck widening and superstructure rehabilitation. Contracts with multiple bridges and/or multiple rehabilitation activities were excluded from the analysis. In total, only 16 bridges were available for this cost analysis during the three year period of 1984-86. No stratified analysis of deck replacement costs could therefore be undertaken.

Table 2.25 Summary of "Other" Deck Reconstruction Cost

(a) Descriptive Statistics on Transformed Values (by Log_{10})

Count	Mean	Standard Deviation	Standard Error	Min.	Max.	95%CI*
79	2.060	0.254	0.0286	1.512	2.623	2.003 to 2.117

* 95%CI = 95% confidence interval of the mean

** Kolomogorov D-statistic = 0.039, Probability = 0.15 < α = 0.05

(b) Values in Percentage

Mean* (%)	Min.** (%)	Max.** (%)	95%CI* (%)
114.75	32.51	420.17	100.69 to 130.91

* Converted from the results shown in (a)

** Raw data values

Table 2.26 shows the summary of deck replacement cost analysis. The distribution of unit deck replacement costs and the "other" deck replacement costs were found to be normally distributed according to the Shapiro-Wilkes W-statistic being significant at a 5% significance level, as shown in Table 2.26-(a). The mean deck replacement unit cost was $42.02 per square foot and its 95% confidence interval was $33.48 to $50.66. Compared with the mean deck reconstruction cost, this value is very large. The mean deck reconstruction unit cost was $10.64 per square foot and its 95% confidence interval ranged from $9.22 to $12.06.

The "other" cost was expressed in percentage of the bridge item cost. The bridge item cost of deck replacement included cost items which were directly related to the structure, and other costs included such items as traffic maintenance and mobilization costs. As shown in Table 2.26-(b), the range was wide with a minimum value of 48.11% and a maximum value of 194.47%. The mean value was 113.95% and the 95% confidence interval was between 89.17% and 138.73%. For a life-cycle cost analysis, a random value approach can be applied to deal with this wide range of the 95% confidence interval when a large number of bridges are analyzed for estimating future rehabilitation expenditures.

2.3.8 Summary of Rehabilitation Cost Analysis

It was found that the current system of recording bridge rehabilitation projects in Indiana was not consistent, and the development of unit costs on the basis of present grouping was difficult. A new system of classification of bridge rehabilitation projects is necessary to develop a consistent and

Table 2.26 Summary of Deck Replacement Cost Analysis

(a) Unit Cost for Bridge Item Cost Category ($ per square foot)

Count	Mean	Standard Deviation	Standard Error	Min.	Max.	95%CI*
16	42.02	16.03	4.007	20.35	72.70	33.48 to 50.66

* 95%CI = 95% confidence interval of the mean

** Shapiro-Wilkes W-statistic = 0.894; Probability = 0.068 > α = 0.05

(b) "Other" Deck Replacement Cost (As Percentage of the Bridge Item Cost Category)

Count	Mean	Standard Deviation	Standard Error	Min.	Max.	95%CI
16	113.95	46.51	11.628	48.11	194.47	89.17 to 138.73

* 95%CI = 95% confidence interval of the mean

** Shapiro-Wilkes W-statistic = 0.933; Probability = 0.335 < α = 0.05

useful set of unit costs that can be used for planning purposes.

Bridge rehabilitation is site specific. Therefore, there is a large variability in amount of work done in each rehabilitation project. Statistical analyses were conducted for two major rehabilitation alternatives, deck reconstruction and deck replacement. The analyses resulted in a stratified list of unit bridge item costs for the deck reconstruction and overlay alternative. The resulting unit costs found in Tables 2.22 and 2.23 should provide better cost estimates than the single mean rehabilitation unit cost presently used. These unit costs reflect only the expenditures directly related to the structural components of deck reconstruction. All other indirect costs, such as traffic maintenance and mobilization costs, were grouped into the "other" cost group. The "other" deck reconstruction cost was computed as a percentage of the bridge item cost (see Table 2.24). Results of this analysis can be used to estimate the total deck reconstruction cost in the future. A stratified statistical analysis of deck replacement cost could not be performed due to the lack of sufficient data. However, it was observed that there is a significant difference in unit costs between deck replacement and deck reconstruction alternatives (see Table 2.26). It is not, therefore, proper to represent rehabilitation costs by a single average unit cost, as it is the present custom. Deck replacement can be used as an alternative to deck reconstruction by making a trade-off analysis, because timings of implementing these two alternatives are different, as discussed in Chapter 3.

2.4 Bridge Maintenance Cost Analysis

2.4.1 Background

The bridge maintenance activity was defined in this study according to

the categories of activities listed in the Indiana Field Operations Handbook for Foremen [IDOH 1985-86]. Currently, five activity types are used to group and record bridge maintenance work. Activities in this category are force-account, in-house maintenance work performed by state highway employees of subdistricts and/or districts. Accomplishments of maintenance activities, together with information on labor and material, are recorded by way of a job recording card, called a crew-day card. Crew-day cards are gathered by each district and eventually sent to the central office for preparing statewide maintenance work summary reports by the Division of Maintenance. These reports, along with information on unit costs for labor, material, and equipment supplied by the Maintenance Division, served as a resource for this bridge maintenance cost analysis. The maintenance summary reports are available at the subdistrict level for each bridge maintenance activity. Records are customarily summarized by highway type (interstate and other state highway) within a subdistrict. The current procedure of keeping track of bridge maintenance does not require maintenance workers to record on the crew-day card the specific locations of bridges maintained. Therefore, it was necessary to use average values at the subdistrict level to determine representative bridge maintenance costs.

2.4.2 Maintenance Needs and Activity Types

Table 2.27 shows the average bridge deck areas by subdistrict and by district computed using the 1985-86 maintenance summary reports. As for bridges on interstates, Gary subdistrict had the largest average deck area and Rensselaer subdistrict the smallest. Similarly, for bridges on other state

Table 2.27 Distribution of Bridge Deck Areas by Subdistrict

District	Subdistrict	Interstate			Other State Highways		
		Number of Bridges	Bridge Deck Area (yd^2)	Avg. Deck Area (yd^2)	Number of Bridges	Bridge Deck Area (yd^2)	Avg. Deck Area (yd^2)
Crawfordsville	Terre Haute	49	45,653	931.3	95	66,449	699.5
	Crawfordsville	56	31,725	566.5	86	23,847	277.3
	Fowler	36	41,582	1155.1	86	50,073	582.2
	Frankfort	42	33,323	793.4	92	26,213	284.9
	Greencastle	48	30,793	641.5	95	37,998	400.0
	Veedersburg	22	21,094	958.8	108	49,709	460.3
	Craw. Dist.	253	204,152	806.9	562	254,289	452.5
Ft. Wayne	Warsaw	—	———	———	72	24,050	334.0
	Goshen	—	———	———	77	23,483	305.0
	Fort Wayne	34	24,895	732.2	60	42,701	711.7
	Angola	37	31,460	850.3	48	14,088	293.5
	Wabash	19	11,520	606.3	105	54,146	515.7
	Bluffton	16	20,153	1259.6	67	23,889	356.6
	Ft. Wayne Dist.	106	88,028	830.5	429	182,357	425.1
Greenfield	Indianapolis	293	487,261	1663.0	37	48,067	1299.1
	Greenfield	59	39,014	661.3	67	34,959	521.8
	Centerville	68	48,290	710.1	119	64,474	541.8
	Anderson	61	41,500	680.3	68	34,995	514.6
	Tipton	—	———	———	72	35,469	492.6
	Ridgeville	—	———	———	92	45,807	497.9
	Greenfield Dist.	481	616,065	1280.8	455	263,771	579.7
LaPorte	La Porte	24	20,366	846.6	45	22,036	489.7
	Monticello	—	———	———	87	52,223	600.3
	Plymouth	—	———	———	64	48,991	765.5
	Rensselaer	36	18,166	505.2	72	19,197	266.6
	Valparaiso	25	34,116	1364.7	59	56,751	961.9
	Winamac	—	———	———	69	25,613	371.2
	Gary	98	219,596	2240.8	60	86,706	1445.1
	La Porte Dist.	183	292,266	1597.1	456	311,517	683.2
Seymour	Aurora	25	46,699	1868.0	76	37,316	491.0
	Bloomington	—	———	———	130	66,571	512.1
	Columbus	84	64,991	773.7	96	43,536	453.5
	New Albany	86	128,058	1489.0	99	61,864	624.9
	Madison	—	———	———	84	23,477	279.5
	Seymour	47	46,068	980.2	139	68,299	491.4
	Seymour Dist.	242	285,816	1181.1	624	301,063	482.5
Vincennes	Linton	—	———	———	97	39,034	402.4
	Dale	16	15,255	953.4	100	40,291	402.9
	Evansville	41	51,133	1247.1	115	124,746	1084.7
	Paoli	—	———	———	75	41,741	556.5
	Branchville	23	24,019	1044.3	58	35,050	604.3
	Petersburg	—	———	———	133	110,394	830.0
	Vincennes Dist.	80	90,407	1130.1	578	391,256	676.9
	Statewide Total	1345	1,576,734	1172.3	3104	1,704,253	549.1

highways, Gary subdistrict had the largest average deck area and Rensselaer subdistrict the smallest. Assuming that the amount of maintenance is proportional to the total deck area, Table 2.27 indicates a possibility of a large variation in potential bridge maintenance needs among subdistricts, provided that the distribution of bridge condition levels is the same for all subdistricts.

In the maintenance management system of the Indiana Department of Transportation, there are five types of bridge maintenance activities. These five activities include hand cleaning of bridges, bridge repairs, deck flushing, patching, and other bridge maintenance. Table 2.28 gives the descriptions of the five activity types found in the Field Operations Handbook for Foremen [IDOH 1985-86]. The hand cleaning and flushing are done annually for each bridge. The remaining three activities are done whenever needs arise or as recommended by bridge inspectors.

2.4.3 Study Approach and Data Base

It was decided to use average values by subdistrict to compile data base for maintenance cost analysis, because it was not possible to construct a maintenance history for specific bridges. The data base was constructed using the annual accomplishment and performance summary reports of the past 6 years, from fiscal year 1980-81 through 1985-86. From data sets, information on the amount of work done, number of man-hours required, and number of crew-days spent for the five activities were obtained. Cost data were taken from the 1985-86 reports; hence, unit costs computed were considered to be closer to the 1985 price. Cost data consisted of three elements: labor, material, and

Table 2.28 Description of Current Bridge Maintenance Activity Types

Activity Code	Activity Type	Description and Purpose
241	Hand Cleaning Bridges	Cleaning of bridge deck surfaces, expansion joints, drain holes, bridge seats and sidewalks by hand shoveling, sweeping and air blasting to remove accumulation of sand, chemicals and debris.
243	Bridge Repair	Minor repairs to bridge structures including repair, replacement or painting of handrails, curbs or sidewalk repair, minor joint and deck repair, timber deck repair, support repair, deck sealing and other minor repairs. Includes emergency deck or support repair and minor maintenance of lift bridges.
244	Flushing Bridges	Cleaning of bridge seats, drain holes, expansion joints, and truss members by flushing to remove accumulation of sand, chemicals and debris.
245	Patching Bridge Decks	Patching of bridge decks using a Portland Cement, concrete or approved epoxy adhesive. Includes marking, sawing and breaking out old concrete with jack hammers.
249	Other Bridge Maintenance Activities	Other routine bridge maintenance activities that are not specifically identified as separate activities.

equipment. The labor cost portion accounted for most of the five activities except for Activity 243 (bridge repair) where labor cost was slightly more than 50% of the total cost. All activities were expressed therefore in terms of man-hours per production unit. At the same time, total maintenance costs of activities were converted into cost per man-hour. The cost per man-hour was then multiplied by the number of man-hours that were required at site to determine unit cost per production unit.

2.4.4 Effects of Management Factors upon Work Requirements

In a previous study on pavement maintenance cost analysis on crack sealing and patching [O'Brien 1985], it was found that the effect of subdistrict as a management factor was not significant for accounting for differences among unit costs of these activities. In the present analysis, an assumption was made that employees of each subdistrict follow the same work standards which are stated in the Field Operations Handbook for Foremen [IDOH 1985-86]. This assumption made it possible to evaluate the effects of other management factors. Originally, it was planned to use the same factors used in the bridge rehabilitation cost analysis. However, the bridge type factor had to be excluded from consideration because crew-day card records do not identify maintenance work by bridge type. The exclusion of this factor, however, did not affect the results, because maintenance works are mostly related to bridge decks, erosion near abutments and waterways, and these factors are mostly independent of the superstructure type. Eventually, effects of highway type and climatic region factors were evaluated. Also tested was the effect of deck area size upon unit costs, because the average deck area varied

significantly among the subdistricts.

Results of the analysis indicated that the only significant factor was the effect of highway type. Table 2.29 gives results of one-way analysis of variance tests performed on the five bridge maintenance activities with highway type as the main effect. When subdistrict level average values were used as sample data, the difference between the work requirements of bridges on interstate and other state highways was statistically significant for Activities 241 and 243. As for Activities 244 and 245, the difference was moderately significant. Highway type was not, however, significant at all for Activity 249. Table 2.29 shows the man-hours needed to do one production unit of a particular type of maintenance activity. This table also shows the 95% confidence interval of the mean and minimum and maximum values found in the data.

One should use caution in interpreting the results shown in Table 2.29. For Activities 241 and 244, the production unit would depend upon the size of the deck. Therefore, work requirements would considerably vary for bridges of different deck areas. On the other hand, man-hour requirements of Activities 243 and 249 are the amount of man-hours to perform these activities in one crew-day. Hence, if a repair requires more than one crew-day, the work requirement for that bridge would have to be adjusted by the number of days. For Activity 245 (patching), however, there is no need of adjustment because the work requirement was computed for each square foot of patching work.

2.4.5 Representative Maintenance Unit Costs

After work requirements were computed in man-hours per production unit, costs of bridge maintenance activities were computed in dollars per man-hour.

Table 2.29 Man-hours Needed for Bridge Routine Maintenance Activities

Activity Type	Production Unit	Interstates	Other State Highways	Significance Level
241. Hand Cleaning Bridges (N = 346)	Man-hours per Deck	Mean = 8.18 SE = 0.21 95%CI = 7.76 to 8.59 Min = 3.73 Max = 17.18	Mean = 6.88 SE = 0.13 95%CI = 6.62 to 7.15 Min = 0.75 Max = 12.57	0.000
243. Bridge Repair (N = 236)	Man-hours per Repair	Mean = 37.85 SE = 2.01 95%CI = 33.82 to 41.88 Min = 16.00 Max = 96.00	Mean = 34.51 SE = 0.75 95%CI = 33.02 to 35.99 Min = 8.00 Max = 80.20	0.058
244. Flushing Bridges (N = 325)	Man-hours per Deck	Mean = 4.97 SE = 0.21 95%CI = 4.55 to 5.40 Min = 0.97 Max = 20.80	Mean = 4.67 SE = 0.13 95%CI = 4.40 to 4.93 Min = 0.93 Max = 10.29	0.207
245. Patching Bridge Decks (N = 194)	Man-hours per Square-foot	Mean = 1.21 SE = 0.12 95%CI = 0.96 to 1.46 Min = 0.05 Max = 4.42	Mean = 1.03 SE = 0.06 95%CI = 0.92 to 1.14 Min = 0.19 Max = 5.00	0.128
249. Other Bridge Maintenance Activities (N = 185)	Man-hours per Maint-nance	Mean = 34.54 SE = 2.25 95%CI = 29.99 to 39.09 Min = 8.00 Max = 64.00	Mean = 33.97 SE = 1.30 95%CI = 31.39 to 36.55 Min = 8.00 Max = 96.00	0.835

Note:
N - Number of samples
M - Mean value
SE - Standard error of the mean
95%CI - 95% confidence interval of the mean
Min - Minimum value found in the data set
Max - Maximum value found in the data set

Data related to standard requirements of labor, material, and equipment were obtained, along with their costs, from the Maintenance Division. These costs were then divided by the number of man-hours to compute unit costs in dollars per man-hour. Results of this computation are found in Table 2.30. Values in the table indicate how much maintenance money is needed for each man-hour to perform the listed five activities. Cost estimates used for the fiscal year 1985-86 were used to compute the unit costs per man-hour. There was a slight difference between the unit costs of maintenance activities for bridges on interstates and other state highways.

After unit cost per man-hour for each maintenance activity was computed, the amount of accomplishment per production unit, given in man-hours, was multiplied by the unit cost per man-hour to obtain the unit cost to implement the maintenance activity. Table 2.31 shows the unit costs of maintenance activities computed in this manner using the 1985 price. The table also shows the 95% confidence intervals of the mean unit costs. The hand cleaning and flushing activities are recorded by the number of decks worked in the year, and specific locations of the bridges that received that activities are not given. Therefore, the values represented in the table are for an average deck size. An estimate of actual deck cleaning and bridge flushing costs can be computed by multiplying the unit costs found in Table 2.31 by the ratio of the actual bridge size to the state average deck size. Figure 2.13 shows estimated costs to clean one deck and Figure 2.14 shows costs to flush one bridge. If a certain bridge requires more than one crew-day for doing Activities 243 and 249, the unit costs shown in Table 2.31 should be multiplied by the number of days needed. For patching, the unit costs shown in the table can be directly used.

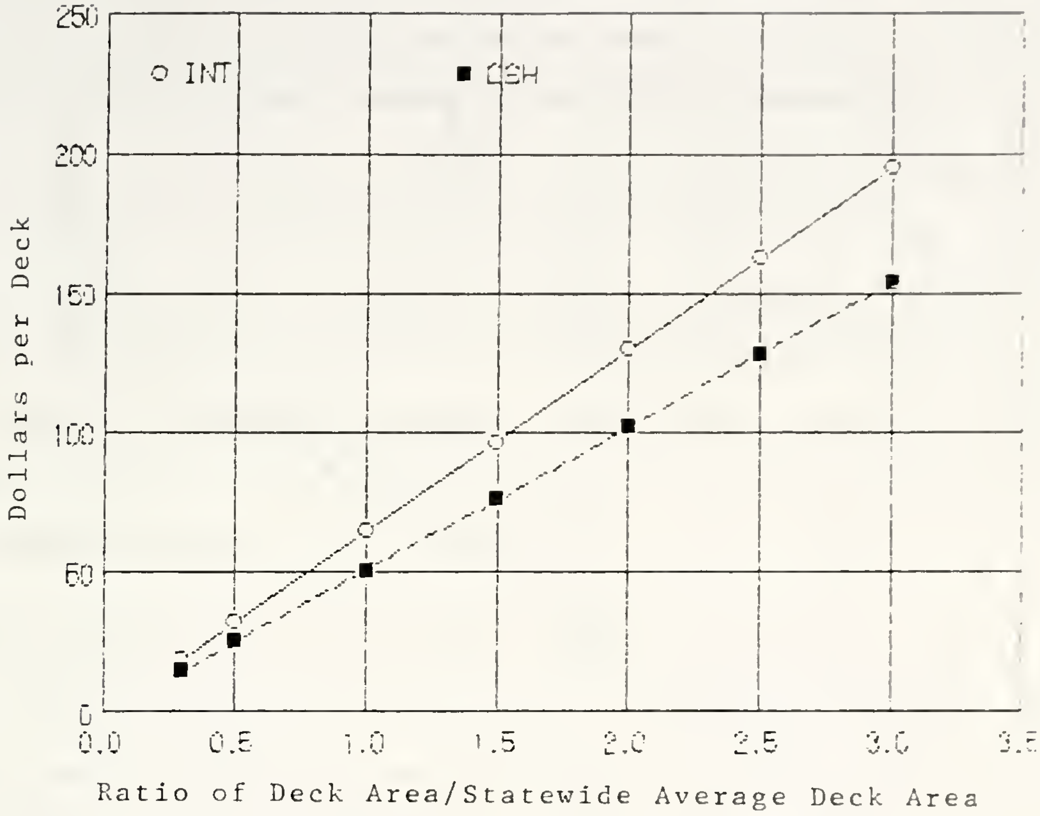
Table 2.30 Unit Costs of Bridge Maintenance Activities Expressed in Dollars per Man-hour (Fiscal Year 85-86)

Activity No.	Activity	Unit Cost in $/Man-hour			
		Labor	Equipment	Materials	Total
(a) Bridges on Interstates (INT)					
241	Hand Cleaning Bridges	7.28	0.65	-	7.93
243	Bridge Repair	7.48	0.58	4.18	12.24
244	Flushing Bridges	7.31	0.47	-	7.78
245	Patching Bridge Deck	7.36	1.23	1.45	10.04
249	Other Br. Maint.	9.09	0.72	1.16	10.97
(b) Bridges on Other State Highways (OSH)					
241	Hand Cleaning Bridges	6.80	0.65	-	7.45
243	Bridge Repair	7.00	0.58	5.63	13.21
244	Flushing Bridges	6.84	0.47	-	7.31
245	Patching Bridge Deck	7.36	1.23	1.45	10.04
249	Other Br. Maint.	8.50	0.27	1.16	9.93

Table 2.31 Unit Costs of Bridge Maintenance Activities Expressed in Dollars per Production Unit (Fiscal Year 85-86)

Activity Type	Production Unit	Interstates	Other State Highways
241. Hand Cleaning Bridges	Per Deck	Mean = 64.87 95%CI = 61.54 to 68.12	Mean = 51.26 95%CI = 49.32 to 53.27
243. Bridge Repair	Per Repair	Mean = 463.28 95%CI = 413.96 to 512.61	Mean = 455.87 95%CI = 436.19 to 475.43
244. Flushing Bridges	Per Deck	Mean = 38.67 95%CI = 35.40 to 42.01	Mean = 34.14 95%CI = 32.16 to 36.04
245. Patching Bridge Decks	Per Square Foot	Mean = 12.15 95%CI = 9.64 to 14.66	Mean = 10.34 95%CI = 9.24 to 11.45
249. Other Bridge Maintenance Activities	Per Maintenance	Mean = 378.90 95%CI = 329.00 to 428.82	Mean = 337.32 95%CI = 311.70 to 362.94

Note: M - Mean value
95%CI - 95% confidence interval of the mean



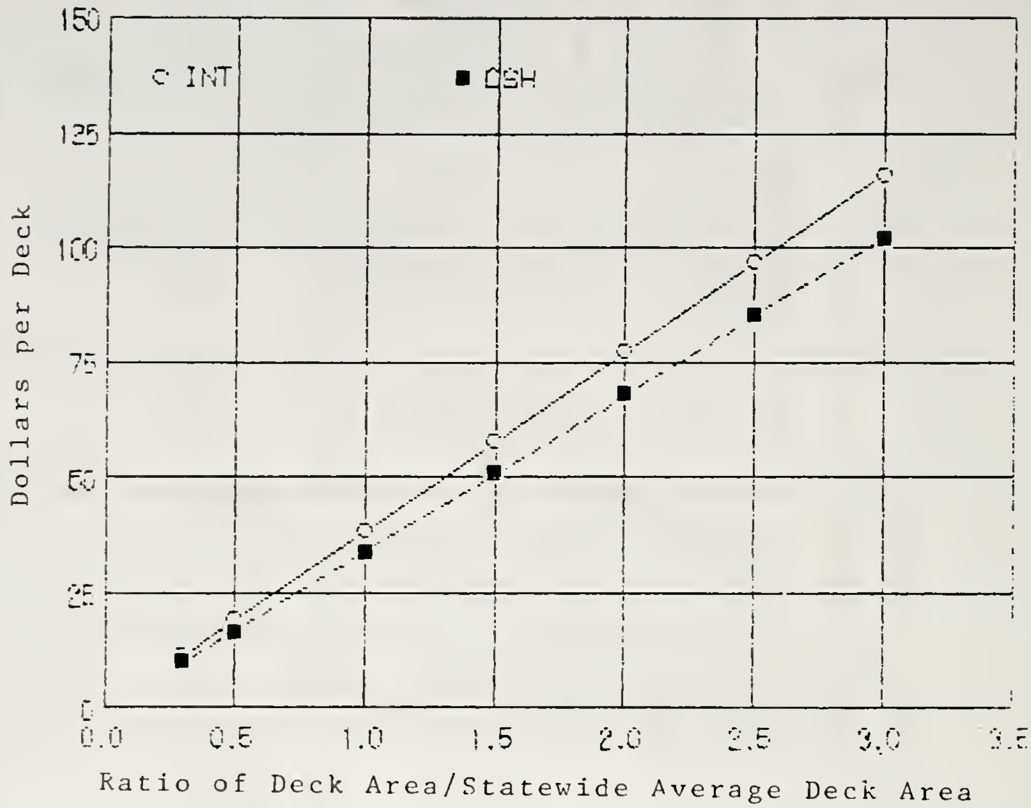
Interstate (INT):

$$\text{Cost per Deck} = \frac{\text{Deck Area } (yd^2)}{1{,}172.3 \ (yd^2)} \times (\$64.87)$$

Other State Highways (OSH):

$$\text{Cost per Deck} = \frac{\text{Deck Area } (yd^2)}{549.1 \ (yd^2)} \times (\$51.26)$$

Figure 2.13 Cost of Activity 241 (Hand Cleaning Bridges) in Dollars per Deck



Interstate (INT):

$$\text{Cost per Deck} = \frac{\text{Deck Area } (yd^2)}{1{,}172.3\ (yd^2)} \times (\$38.67)$$

Other State Highways (OSH):

$$\text{Cost per Deck} = \frac{\text{Deck Area } (yd^2)}{549.1\ (yd^2)} \times (\$34.14)$$

Figure 2.14 Cost of Activity 244 (Flushing Bridges) in Dollars per Deck

2.4.6 Suggestions for Bridge Maintenance Record Keeping

The current record keeping procedure by means of crew-day cards may be sufficient for a statewide highway maintenance management system. However, to be useful to bridge management system, the existing maintenance record keeping system is not satisfactory. By identifying maintenance information by specific bridge, the current bridge management program can be greatly upgraded, particularly in the area of life-cycle cost analysis. If more than one bridge is involved in one crew-day card, the information of each of these bridges should be separately recorded. With these improvements, bridge maintenance information can be easily transferred to the data base of the bridge management system.

Another suggestion is to breakdown Activity 243 (bridge repair) and Activity 249 (other bridge maintenance) into smaller groups. A manual search of crew-day cards for the fiscal year 1986-87 revealed that these activity groups included some repair works that could be singled out as separate activities. Table 2.32 shows types of activities recorded as Activity 243. Among them, minor bridge deck repair, rail and post repair, and joint repair seemed to take place frequently. Table 2.33 gives types of activities recorded as Activity 249. Repair works included in this activity are primarily peripheral to the bridge structure. Among them, repairs of washout caused by erosion and clearing of the waterway can be singled out since these works took place frequently and may require an entire crew-day. Based on these observations, a suggested list of maintenance activity groupings was made and shown in Table 2.34. These groupings should help bridge managers to keep track of maintenance activities performed to particular bridges.

Table 2.32 Bridge Maintenance Activities Categorized as Activity 243: Bridge Repair

Repair Item	Frequency	Percent (%)
Minor Bridge Deck Repair	78	35.0
Repair/Replacement of Bridge Rails and Posts	53	23.8
Joint Repair	49	22.0
Bridge Support Repair	8	3.6
Minor Abutment Repair	6	2.7
Box Culvert Repair	5	1.8
Riprap Placement	3	1.3
Minor Pile Repair	3	1.3
Repair/Replacement of Drainage	2	0.9
Washout Repair Near Bents	2	0.9
Refastening of Steel Plate Joints	2	0.9
Others	8	3.6
Total	223	100.0

Table 2.33 Bridge Maintenance Activities Categorized as Activity 249: Other Bridge Maintenance

Maintenance Item	Frequency	Percent (%)
Repairing Washouts and Other Water-Eroded Areas by Placing Riprap	92	33.7
Clearing Waterway	69	25.3
Re-Painting Bridge Numbers	56	20.5
Assisting the Inspection of Bridges	14	5.1
Deck Repair Including Preparation	9	3.3
Repairing Mud Walls and Retaining Walls	5	1.8
Beautification of Bridges (Erasing Graffiti)	5	1.8
Repairing Bridge Channel	4	1.5
Repairing Abutment Footings	3	1.1
Drainage Repair	2	0.7
Cleaning Joints and Bridge Seats	2	0.7
Repairing Steel Plates by Welding	2	0.7
Others	10	3.7
Total	273	100.0

Table 2.34 Suggested Bridge Maintenance Activity Groups

Code	Activity	Production Unit
240	Hand Cleaning Bridges	Number of Bridges
241	Flushing Bridge Decks	Number of Decks
242	Bridge Patching	Square foot
243	Bridge Railing Repair	Man-hour
244	Expansion Joint Repair	Number of Joints
245	Minor Deck Repair	Man-hour
246	Other Bridge Repair	Man-hour
	May include: a. Minor abutment repair b. Minor pile and pier repair c. Repair/replacement of drainage parts d. Refastening of steel plate joints e. Repair of steel plates by welding	
247	Washouts Repair	Man-hour
248	Cleaning Waterway	Man-hour
249	Other Bridge Maintenance	Man-hour
	May include: a. Bridge channel repair b. Drainage repair c. Cleaning joints or bridge seats	

Maintenance records can then be integrated with bridge improvement records to provide necessary data for a useful life-cycle analysis.

2.4.7 Summary on Maintenance Cost Analysis

Unit costs of five routine bridge maintenance activities were determined using the amount of man-hours needed as a variable. It was found that there are some differences in the unit costs between maintenance activities performed on interstate highways and other state highways. A manual inspection of crew-day cards revealed that some bridge maintenance works need to be redefined. A list of suggested maintenance categories and their code numbers was prepared.

CHAPTER 3

TIMING FOR BRIDGE REPLACEMENT, REHABILITATION, AND MAINTENANCE

3.1 Background

For life cycle cost analysis, a reasonable estimate of the timing for future bridge repair activities is necessary. This chapter presents results of the analysis that examined the timing of various bridge activities. For this purpose the information from Bridge Rehabilitation Records maintained by the Indiana Department of Transportation was primarily used.

3.2 Timing for Bridge Replacement

Using the Bridge Rehabilitation Records file, bridges which were replaced between 1981 and 1985 were examined. This file records the dates of replacement, major rehabilitation, and widening. Data collected included year of construction, bridge age at replacement, bridge type (concrete and steel), average daily traffic (ADT), condition rating of deck, superstructure, and substructure, and rehabilitation information. Condition rating data were extracted from the bridge inspection data file.

3.2.1 Number of Years Passed

Among the bridges replaced during this period, one hundred and five (105) bridges were selected for subsequent analyses. They were all bridges on other state highways. No interstate bridge was replaced during the period. For this analysis, the three management factors used for the rehabilitation cost analyses were considered, climatic region, bridge type, and traffic level. Table 3.1 summarizes average bridge life for the two climatic regions and two bridge types. Only a small difference was observed in bridge lives among the groups. The mean bridge life in the southern region was 52.96 years and that in the northern region was 52.53. There was no significant difference between the regions in the 95% confidence interval of the mean. As for bridge type grouping, there was no significant difference in bridge life between concrete and steel bridges. Both bridge groups had approximately fifty-two years of mean bridge life.

Prevailing traffic, especially truck traffic, is believed to affect bridge life. Bridge lives of the selected (105) bridges were plotted as a function of the 1985 average daily traffic (ADT). Figure 3.1 shows the result of scatter plot. The plot indicates that a regression relationship does not exist between bridge life and traffic volume. Bridge data points were normally distributed around the overall mean value of approximately 52.74. A linear regression analysis on bridge life with ADT as a predictor variable showed that the slope of the regression is not statistically significant at a 5% significance level for the sample data set.

Another point of concern is the difference in the mean lives of bridges

Table 3.1 Comparison of Bridge Lives (Years) by Region and by Bridge Type

(a) Comparison by Climatic Region

Group	Count	Mean	Standard Deviation	Standard Error	Min.	Max.	95%CI*
North	53	52.53	5.81	0.798	39.00	65.00	50.92 to 54.13
South	52	52.96	5.74	0.796	41.00	71.00	51.36 to 54.56

* 95%CI = 95% confidence interval of the mean

(b) Comparison by Bridge Type

Group	Count	Mean	Standard Deviation	Standard Error	Min.	Max.	95%CI*
Concrete	75	52.91	5.84	0.674	39.00	65.00	51.56 to 54.25
Steel	30	52.33	5.61	1.024	45.00	71.00	50.24 to 54.43

* 95%CI = 95% confidence interval of the mean

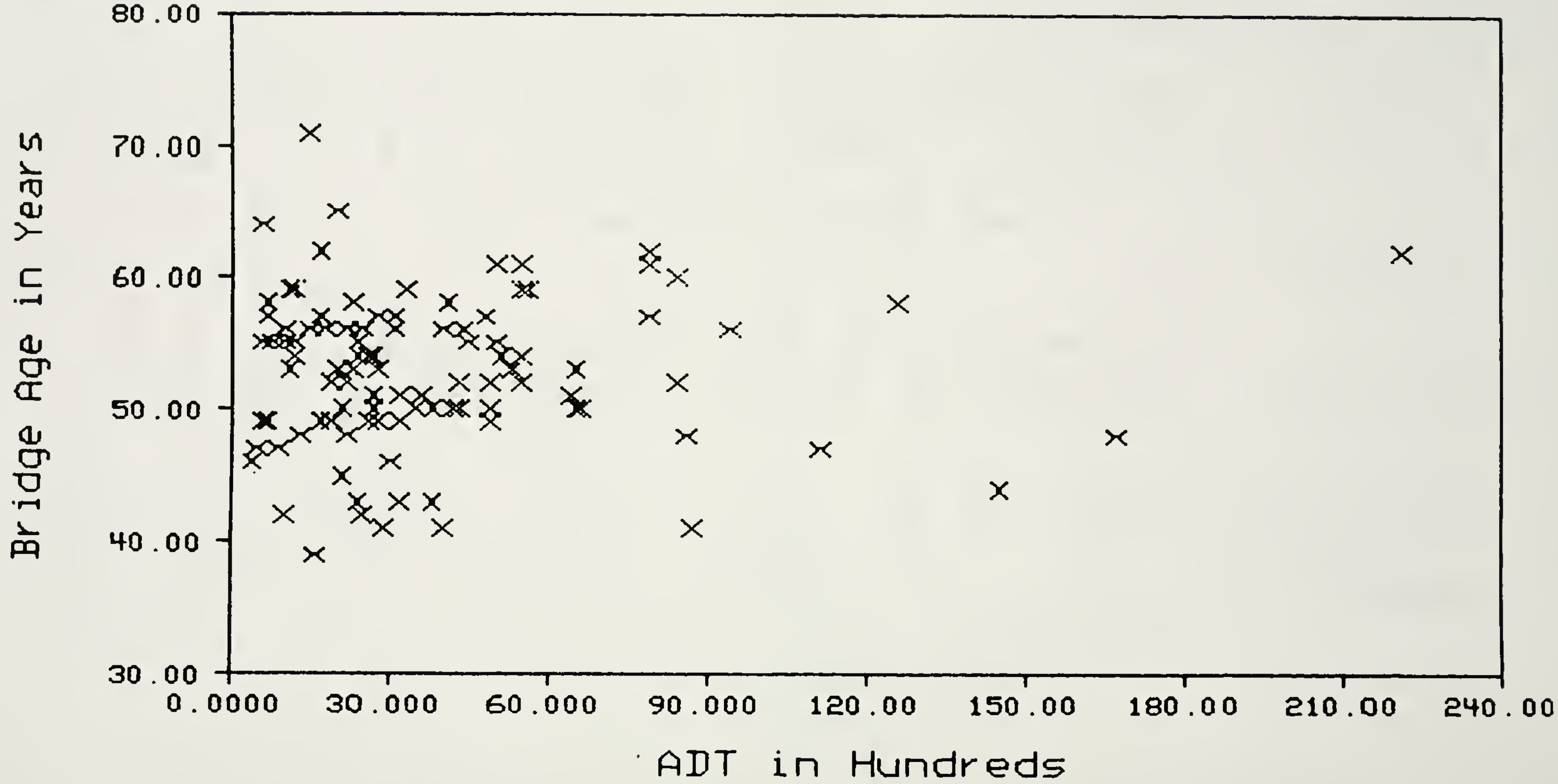


Figure 3.1 Bridge Life vs. Average Daily Traffic (ADT)

which had major rehabilitation and/or widening works and those which had neither of these improvement activities. A one-way analysis of variance was performed on bridge lives of these two groups. The assumption of homogeneity of variance was met because the Cochran´s C-statistics was 0.639 and its significance was 0.042, which was greater than α = 0.001. Therefore, there was no need of transforming raw data for performing an analysis of variance. Table 3.2 and Table 3.3 give a summary of analysis on these two groups. The ANOVA table in Table 3.2 shows that the difference in mean bridge lives of the two groups was significant at a 95% confidence level (α = 0.05) with significance probability of 0.0003. Bridges which were rehabilitated once had a mean life of about 55 years and bridges which had no history of major rehabilitation had a mean life of about 51 years. The difference was four (4) years and the 95% confidence intervals of the two means did not overlap, as shown in Table 3.3. The Kolomogorov D-statistic shown in Table 3.3 was used to test the null hypothesis that the input data values were a random sample from a normal distribution. Since the computed probability was 0.15, the null hypothesis was accepted at a 95% confidence level. This result was consistent with the result shown in the ANOVA table in Table 3.2; The mean bridge lives of the improved and non-improved bridges were statistically different.

3.2.2 Condition Ratings at the Time of Replacement

Along with the bridge life, condition ratings of bridge deck, superstructure, and substructure at the time of replacement were examined separately for concrete and steel bridges. Figure 3.2 compares the ratings of the three bridge components within each bridge group. As shown in the figure, not much difference was observed between the two groupings. Nearly two-thirds of the

Table 3.2 Results of Analysis of Variance on Bridge Lives (Years) With and Without Major Improvements

Source	d.f.	SS	MS	F-Ratio	Significance
Between Groups	1	415.92	415.92	14.15	0.0003
Within Groups	103	3028.13	29.40		
Total	104	3444.05			

Cochran's C-statistic = 0.6392,
Probability = 0.042 (approx.) > α = 0.001

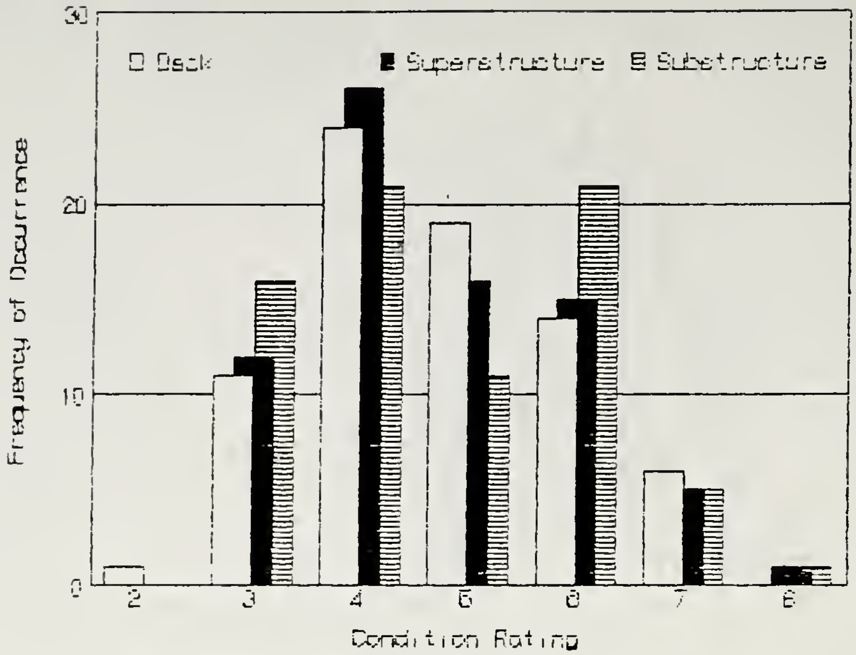
Note: d.f. = Degrees of freedom
SS = Sum of squares
MS = Mean squares

Table 3.3 Descriptive Statistics on Bridge Lives in Years for Replaced Bridges

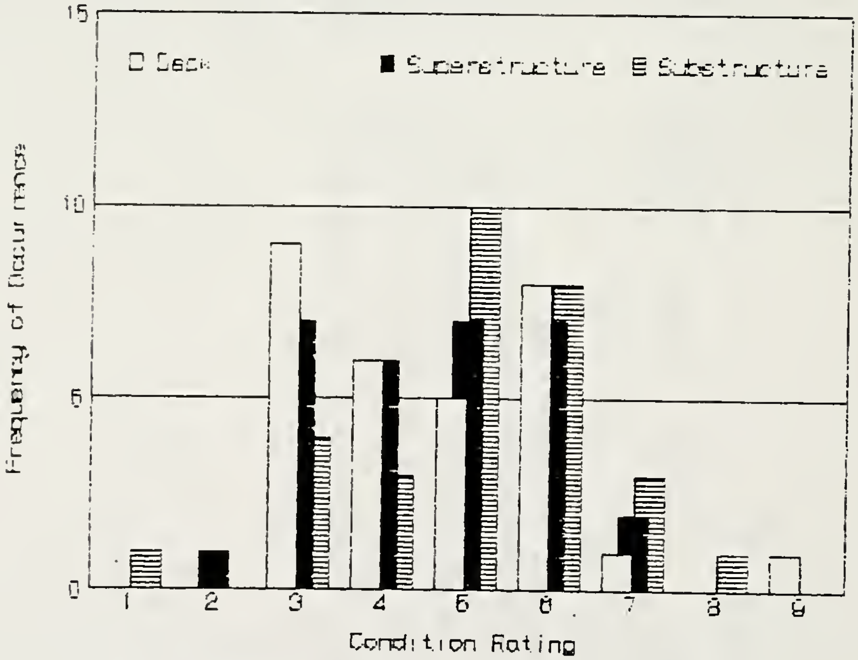
Group	Count	Mean	Standard Deviation	Standard Error	Min.	Max.	95%CI*
Without Improvement	47	50.53	4.54	0.662	41.00	62.00	49.20 to 51.86
With Improvement	58	54.53	6.04	0.793	39.00	71.00	52.95 to 56.12
All**	105	52.74	5.75	0.562	39.00	71.00	51.63 to 53.86

* 95%CI = 95% confidence interval of the mean

** Kolomogorov D-statistic = 0.067, Probability = 0.15 > α = 0.05



(a) Concrete Bridges



(b) Steel Bridges

Figure 3.2 Distribution of Condition Rating at the Time of Bridge Replacement

bridges had condition ratings less than or equal to 5 at the time of replacement. The remaining one-third of bridges were rated as 6 or higher. Caution should be exercised to interpret these condition rating distributions, because the plots in Figure 3.2 did not discount the effect of repair and rehabilitation activities that might have taken place during the life of a bridge. It should be also understood that decisions for replacing bridges may not only be affected by condition rating but also by some other factors, such as bridge age and alignment of the approach road.

The analysis on bridge replacement timing showed that the current practice of assuming 50 years as the replacement cycle is close to what has been used in the past and this number can therefore be taken as a starting point for life-cycle cost analysis. A summary of descriptive statistics on all of 105 bridges used in the analysis is found in Table 3.3. The table also provides descriptive statistics for bridges with and without history of improvements. It was found that the sample data were normally distributed and the given statistics provided a meaningful description of the sample distribution. The mean bridge life was found approximately 53 years, and the 95% confidence interval of the mean ranged from 52 to 54 years.

3.3 Timing for Major Rehabilitation Works

Two major rehabilitation alternatives were considered for this analysis, deck reconstruction and deck replacement. Under the deck reconstruction category, part of the deck is repaired by shallow and/or full depth patching, and the surface overlaid. Some other items may be repaired as well, such as expansion joints and railings. However, the entire deck is not replaced under

this category. The deck replacement, on the other hand, is the replacement of the entire deck with a completely new one. This work may be accompanied by some superstructure rehabilitation, partial or whole, and/or widening of deck and superstructure. Often, concrete slab bridges are replaced with precast-beam bridges. As illustrated in the cost analysis section, unit cost ($\$/ft^2$) of replacement is more than twice as costly as that of deck reconstruction.

3.3.1 Deck Reconstruction

Bridge inspectors may be influenced by classification factors, such as highway type and traffic volume, as well as the level of deck deterioration when they select the deck reconstruction and overlay work. Two management parameters, the number of years passed before the time of the first deck reconstruction and overlay and the percent of deck area needing patching, were examined in this analysis. For analyzing the timing and the effect of deck area needing patching upon deck reconstruction decision, bridges which had only one deck reconstruction and overlay since the time of their construction, were considered. There were 237 bridges that met this criterion. For analyzing the relationship between condition rating and timing of deck reconstruction, the bridges included in the cost analysis were used.

3.3.1.1 Number of Years Passed

Among the three classification factors (region, highway type, and ADT), only the region was found to be significant. Table 3.4 gives the model and basic statistics to evaluate the analysis results. The resulted significance level was 0.0004 and the regional effect was significant at 5% level, indicating that there was a significant difference between the mean number of years

Table 3.4 Regional Effect on the Timing of Deck Reconstruction and Overlay Activity in Terms of Number of Years Passed from Construction

North	South	Total
N = 121 Mean = 20.3 yrs. SE = 0.64 LL = 19.0 UL = 21.6	N = 116 Mean = 23.5 yrs. SE = 0.65 LL = 22.2 UL = 24.8	N = 237 Mean = 21.9 yrs. SE = 0.45 LL = 21.0 UL = 22.8

Homogeneity Test Significance Level = 0.335 > 0.001
Significance Level = 0.0004 < 0.05

Definitions:

N = Number of samples in the cell
M = Mean number of years passed before the first deck deck reconstruction and overlay
SE = Standard error of the mean
LL = Lower limit of the 95% confidence interval of the mean
UL = Upper limit of the 95% confidence interval of the mean

passed by the time of the first deck reconstruction in the northern region (20.3 years) and that of the southern region (23.5 years). This difference may be attributed to the severe weather and frequent use of de-icing materials in the northern region.

3.3.1.2 Percent of Deck Area Needing Patching

The extent of needed patching is probably an indicator of deck deterioration most obvious to the inspectors in evaluating deck condition. It can be measured at site and it is, in fact, reported in rehabilitation design plans. Using one-way and two-way ANOVAs, effects of classification factors on the selection of the deck reconstruction and overlay alternative were examined in terms of the percent of deck area needing patching. Table 3.5 gives the results of the one-way factor analyses. The climatic region was not significant at 5% significance level ($\alpha = 0.05$), suggesting that inspectors' decisions to select the deck reconstruction and overlay activity were consistent across the regions.

The highway type and ADT level were, however, both significant, as shown in the table. The 95% confidence interval of the expected mean percent patching area for interstate bridges was between 6.20% and 8.00%, when the first deck reconstruction and overlay was undertaken. The confidence interval of the mean percent patching area for bridges on other state highways was between 10.56% and 13.41%. A higher level of deck patching need is tolerated before deck reconstruction is suggested for bridges on other state highways. As for ADT, three factor levels (low, medium, and high) were first considered with 5,000 ADT and 10,000 ADT as the boundary points. However, a two-way ANOVA

Table 3.5 Effects of Region, Highway Type, and Traffic Volume on Selection Deck Reconstruction and Overlay in Terms of Percent of Deck Area Needing Patching

(a) Region

North	South
N = 121 Mean = 9.10% LL = 7.98 UL = 10.37	N = 114 Mean = 9.61% LL = 8.40 UL = 10.99

Homogeneity Test Significance Level = 0.034 < 0.001
Significance Level = 0.570 > 0.05

(b) Highway System

Interstate	Other State Highway
N = 111 Mean = 7.04% LL = 6.20 UL = 8.00	N = 126 Mean = 11.90% LL = 10.56 UL = 13.41

Homogeneity Test Significance Level = 0.002 > 0.001
Significance Level = 0.000 < 0.05

(c) Traffic Volume in ADT

ADT < 10,000	10,000 < ADT
N = 144 Mean = 10.31% LL = 9.16 UL = 11.60	N = 93 Mean = 7.95% LL = 6.86 UL = 9.21

Homogeneity Test Significance Level = 0.110 > 0.001
Significance Level = 0.007 < 0.05

Definitions:

N = Number of samples in the cell
M = Mean percent of deck area needing patching (approximate value because the data were transformed by common logarithm)
LL = Lower limit of the 95% confidence interval of the mean
UL = Upper limit of the 95% confidence interval of the mean

suggested that low and medium ADT levels be combined to provide reliable values. The factor levels were, therefore, regrouped as low (<10,000 ADT) and high (>10,000 ADT) for this analysis. Mean percent patching areas of the two factor levels were significantly different between the two levels as shown in the table. Bridges with high traffic volumes would be likely to have the deck reconstruction and overlay work done at a lower level of deck area needing patching.

As highway type and traffic volume factors were found to be significant, a two-way ANOVA was used to examine the interaction effect of these two factors on percent patching areas. Table 3.6 gives the model and results of this analysis. When highway type was first entered, it was significant at $\alpha = 0.05$ and traffic volume was not significant at the same significance level. However, as the traffic volume factor was entered first, it became significant as well as highway type at $\alpha = 0.05$. The interaction of highway type by traffic volume also became significant at $\alpha = 0.05$, when it was entered first into the model. This indicates that when the percent of deck area needing patching is used as a decision variable, the combination of highway type and traffic volume should be considered to decide on the timing of the deck reconstruction and overlay alternative.

3.3.1.3 Condition Ratings at the Time of Deck Reconstruction

This analysis was done to examine the timing of deck reconstruction and overlay work in terms of condition rating. The selection of this activity is a function of the severity and extent of actual distresses that inspectors may find on bridge decks. Condition ratings are considered to reflect the sever-

Table 3.6 Combined Effects of Highway Type and Traffic Volume on Selecting Deck Reconstruction and Overlay in Terms of Percent of Deck Area Needing Patching as a Decision Variable

		Traffic Volume (ADT)	
		Low ADT < 10,000	High 10,000 < ADT
Highway Type	Interstate	N = 33 Mean = 6.36% LL = 5.03 UL = 8.04	N = 78 Mean = 7.35% LL = 6.31 UL = 8.56
	Other State Highway	N = 111 Mean = 11.90% LL = 10.47 UL = 13.52	N = 15 Mean = 11.94% LL = 8.44 UL = 16.90

Homogeneity Test Significance Level = 0.002 > 0.001

Definitions:

N = Number of Samples
Mean = Mean percent of deck area needing patching (approximate values because the data were transformed by common logarithm)
UL = Upper limit of the 95% confidence interval of the mean
LL = Lower limit of the 95% confidence interval of the mean

ity and extent of distresses. As deck reconstruction is closely related to the deck and superstructure of bridges, condition ratings of these two bridge components were evaluated. Figure 3.3 shows the difference in condition rating distributions of the deck and the superstructure. Condition ratings of decks were mostly 5 and 6 when the deck was reconstructed. However, condition ratings of the superstructure were mostly 6 and 7 at the time of deck reconstruction. This result suggests that the decision about deck reconstruction would be primarily dependent on deck condition rating and not on overall condition rating of a bridge.

3.3.2 Deck Replacement

There were only a few bridges grouped under this category. Within the three year period (1984, 1985, and 1986), only 16 bridges were found to fit the description of this rehabilitation alternative. These bridges had only one deck replacement during their life. No other major rehabilitation work was performed.

3.3.2.1 Number of Years Passed

Figure 3.4 shows the frequency of occurrence for each five-year range. Although there was one extreme case (deck replacement at the 26th year), deck replacement seems to have been undertaken when bridge age was greater than about 40 years. Figure 3.4 also gives the summary statistics of these bridges. The mean number of years passed was 44.6 and the 95% confidence interval level ranged from 41.4 to 47.8 years. When the extreme case of 26 years was excluded from the data set, the mean value became 45.9 with the 95% confidence interval being from 44.2 to 47.7. This result is interesting,

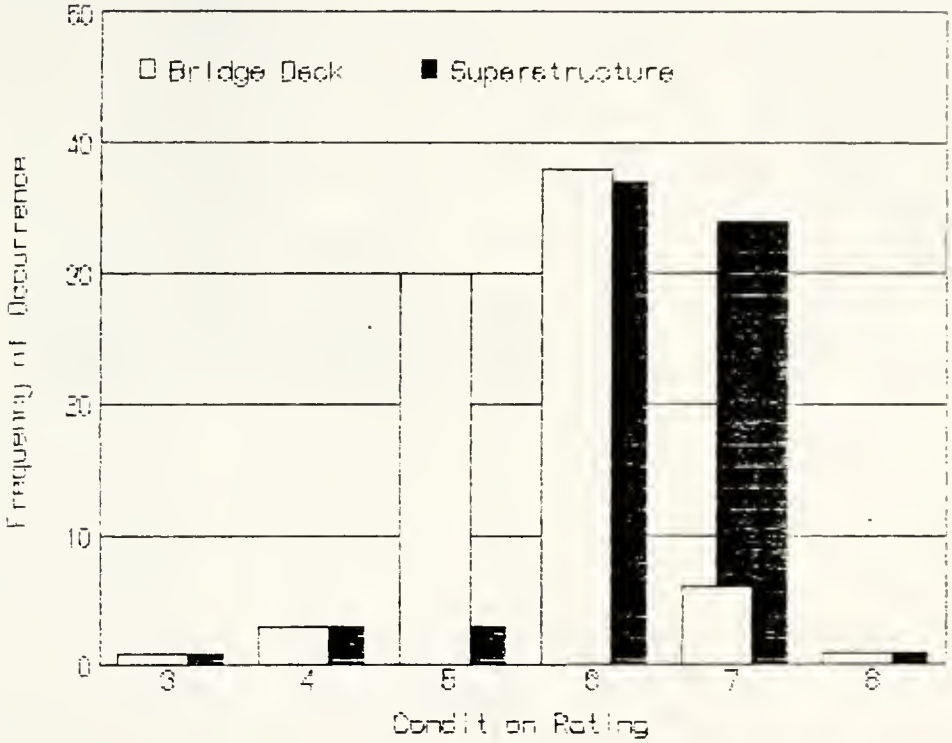
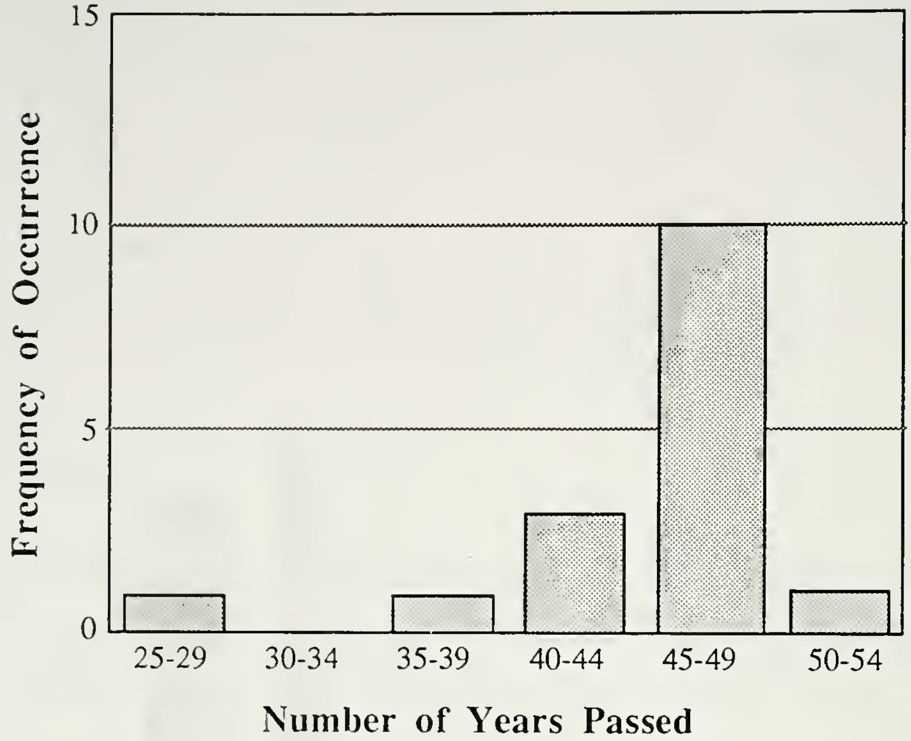


Figure 3.3 Condition Ratings at the Time of Deck Reconstruction



Summary Statistics for Deck Replacement Activity:

Number of Samples = 16
Mean = 44.6 years
Standard Deviation = 6.0 years
Standard Error = 1.5 years
95% Confidence Interval = 41.4 years to 47.8 years

Figure 3.4 Number of Years Passed before the First Deck Replacement Activity

because deck reconstruction is recommended when bridge age is approximately 20 to 22 years after construction. Clearly, there will be a trade-off question between deck reconstruction at an early stage of bridge life and deck replacement at a later year, because the unit costs of these two rehabilitation alternatives are very different.

3.3.2.2 Condition Ratings at the Time of Deck Replacement

Condition ratings at the time of deck replacement were plotted for three components of bridge structure (deck, superstructure, and substructure), as shown in Figure 3.5. Condition ratings of substructure were plotted for comparison with the ratings of deck and superstructure. Figure 3.5 suggests that deck replacement is generally recommended when the condition ratings reach a value of 6 or less. The superstructure may be at a similar condition level. However, the substructure may be not as deteriorated as the deck and superstructure, when deck replacement work is recommended. When the substructure condition rating declines to rating 6 or lower, there is a possibility that other parts are so deteriorated that the replacement of the entire structure may be warranted, as shown in Figure 3.2.

3.4 Timing for Maintenance Work

Most bridge routine maintenance activities are not related to bridge component condition ratings. Maintenance work is conducted at any condition rating as long as it is needed. According to the current data recording system, it is not possible to relate maintenance work to bridge condition. Some works, such as deck cleaning and flushing, are annual events. These are conducted, especially in the northern region of Indiana, to decrease salt

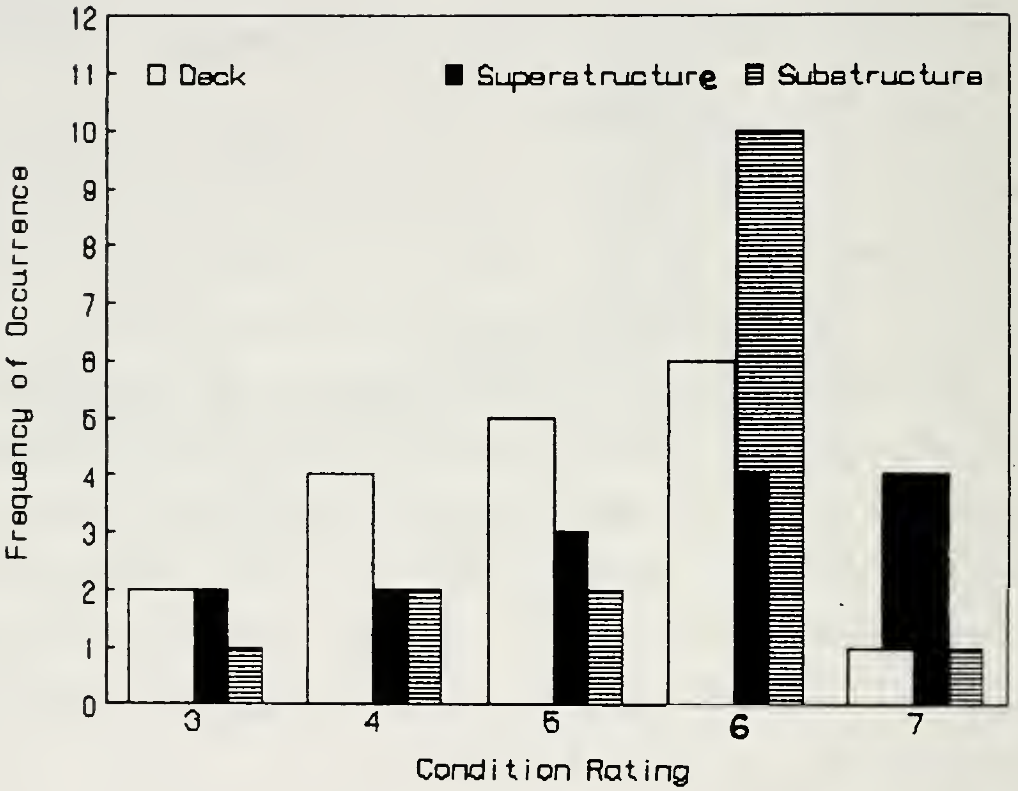


Figure 3.5 Condition Ratings at the Time of Deck Replacement

contamination and possible future damages of the deck induced by debris accumulated in spots like drainage pans and expansion joints. The timing of such activities as bridge repair and patching are difficult to trace because the current recording procedure does not require specific locations of bridges for which maintenance work was performed. Therefore, no time series analysis could be made.

For a network level planning analysis, especially for a life-cycle analysis, the timing for occasional maintenance activities may need to be input based on the opinions of bridge managers. It can be assumed that expenditures for maintenance and repair work would increase as the bridge age increases. However, there is no data base for Indiana bridges to verify this assumption. The current practice of aggregating maintenance information by highway section and by subdistrict does not allow the types of analyses that are required to incorporate maintenance activities with a statewide bridge management system.

3.5 Chapter Summary

An estimate of the timing for future bridge repair expenditures was established and the relationship between condition rating and recommended actions was examined. The results would help bridge managers to conduct a realistic life-cycle cost analysis.

It was found that the assumption of average bridge service life of 50 years was close to what has been used in the past. The statewide average was found to be approximately 52 years. The data used for this analysis did not include interstate bridges. It was found that climatic region and bridge type

may not be a strong factor affecting bridge life. It was difficult to establish a clear relationship between condition rating at the time of replacement and bridge life, because condition ratings are affected by rehabilitation and maintenance activities done during the time period between construction and replacement. Statistical analyses conducted in the present study showed that there was a difference in bridge service lives with and without rehabilitation. However, the average difference observed was only 4 years and the influence of rehabilitation work upon the entire bridge life may be small as far as replacement decision is concerned. Rehabilitation works done on bridges are often related to bridge deck and superstructure and their life spans are shorter than the life span of the entire bridge structure.

As for rehabilitation alternatives, two major activities, deck reconstruction and deck replacement, were considered. It was found that the first deck reconstruction would take place, on the average, approximately 20 years after the initial construction of a bridge. The climatic factor was found to be present and the mean value for the northern region was 20.3 years and that for the southern region was 23.5 years. For deck reconstruction, the deteriorated area needing patching can be used as a factor to determine its need. The analysis showed that the value of the percentage of the deck area in need of patching was affected by factors such as highway type and traffic volume. On the average, bridges on interstates had smaller percentages of deteriorated deck areas when deck reconstruction was recommended. This implies that inspectors tend to allow a higher level of service for interstate highways.

Results of the analysis on deck replacement showed that the average life of bridges before they received the first deck replacement was about 45 years. Very few bridges received deck replacement compared with deck reconstruction. Some bridges received a second deck reconstruction work, but they rarely got a third or fourth. Those bridges that had decks replaced did not receive any other rehabilitation before replacement. Since the difference between the unit costs of deck reconstruction and deck replacement was found to be substantial, a careful trade-off analysis would be necessary to determine the desirable alternative.

No detailed analysis of timing of routine maintenance work could be undertaken in the present study, because the current record keeping procedure does not provide information of maintenance works for specific bridges. Consequently, the timing of these activities need to be entered in a life-cycle analysis on the basis of bridge managers' judgments.

CHAPTER 4

LIFE CYCLE COST ANALYSIS OF BRIDGES

4.1 Background

Bridges last much longer than paved highways. For a highway agency, bridges are a long-term multi-year investment. Throughout its useful life, a bridge requires both routine and periodic maintenance and occasional rehabilitation works. Especially, the deterioration of bridge deck triggers most of maintenance, rehabilitation and replacement works, probably because bridge decks are the most immediate component of a bridge structure that is exposed to the impact of traffic and weather. Bridge decks also are the most visible component of a bridge structure.

Bridges require a series of expenditures for various activities during their life cycles, as shown in Figure 4.1. A life cycle activity profile of a bridge thus can be represented by a series of future bridge works laid out in a cash flow diagram [Hyman and Hughes 1983; Hudson et al. 1987]. It is necessary to make economic decisions with these future expenses in mind. Comparison of projects only in terms of initial investments fails to reflect future funding needs. Life cycle cost analysis has been already applied to

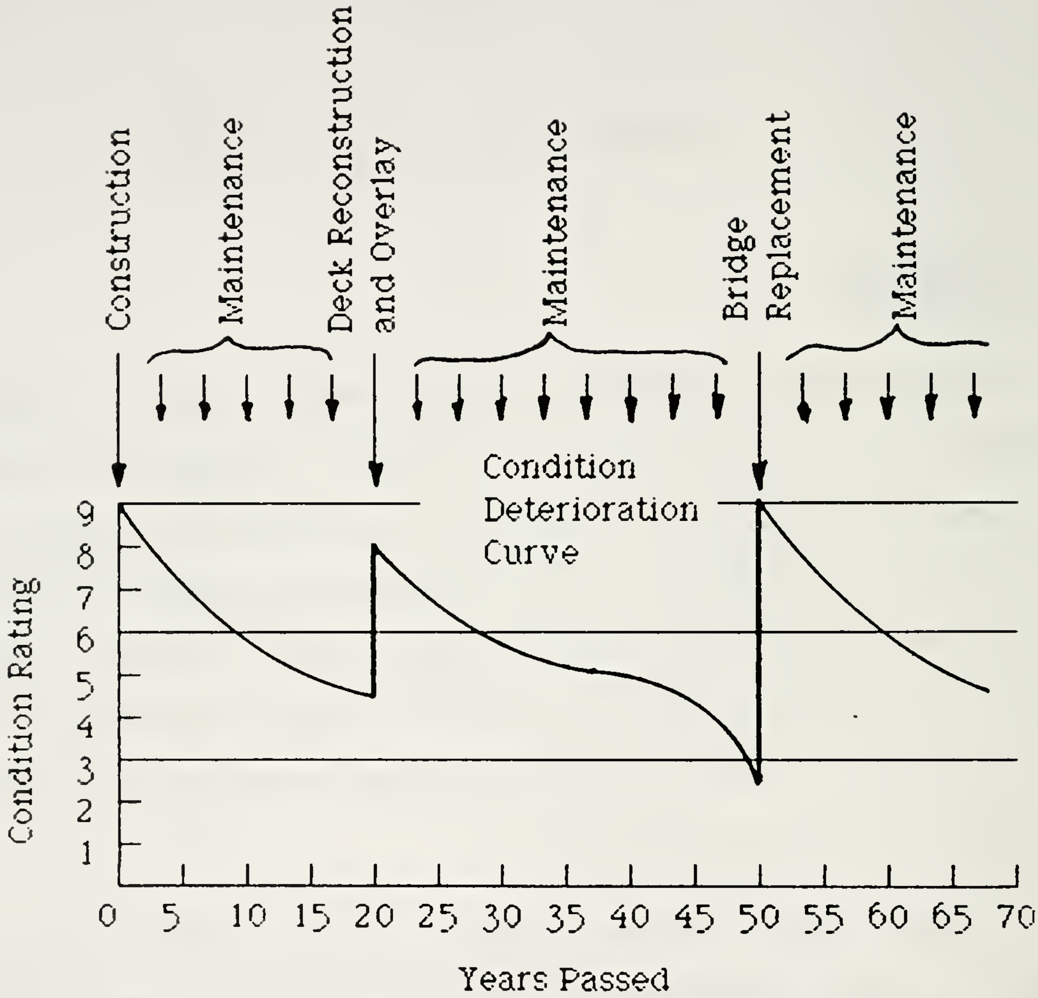


Figure 4.1 Life Cycle of a Bridge

pavement management [Jung 1986; Kulkarni 1984]. Its application to bridge management has been advocated in several recent studies [Hyman and Hughes 1983; Hudson et al. 1987; Weyers et al. 1983; FHWA 1987].

4.2 Purpose and Scope

The purpose of this portion of the study was to establish a standard procedure to perform life cycle cost analysis as a part of the bridge management system for Indiana Department of Transportation. The equivalent uniform annual cost approach was used for this purpose with the consideration of perpetuity of future expenditures. Costs involved in the computation were in terms of constant dollars. Appropriate procedures were developed for both project level and network level analyses. Three sample computations are included in this chapter to demonstrate different applications of the life cycle cost analysis to alternative selection process.

4.3 Agency Cost and User Cost

For a complete life cycle cost analysis, both agency costs and user costs need to be included. Agency costs consist of maintenance, rehabilitation, and replacement costs. In Indiana, bridge routine maintenance is generally performed by INDOT maintenance forces at districts and subdistricts. Rehabilitation works consist of minor and major repair activities which may require the assistance of the Design Division and are let to contractors through the Construction Section. These activities include works such as deck reconstruction and deck replacement. The term bridge replacement is, on the other hand, reserved for a complete replacement of the entire bridge structure. New bridge constructions due to the construction of a new road or a new alignment

are also included in this category.

User costs are primarily attributable to the functional deficiency of a bridge, such as a load posting, clearance restriction, and closure. These functional deficiencies may cause higher vehicle operating costs because of such factors as detours, lost travel time, and higher accident rates. At present, user costs related to functional deficiencies cannot be established because of the limited data. Efforts should be made to develop an appropriate data base so that such user costs can be estimated with a reasonable level of accuracy and incorporated in the life cycle cost analysis. As a proxy for user cost, detour length is at present proposed as a factor for bridge project evaluation, as discussed in Volume 5 of this report.

4.4 Elements of Life Cycle Cost Analysis

4.4.1 Use of Equivalent Uniform Annual Cost

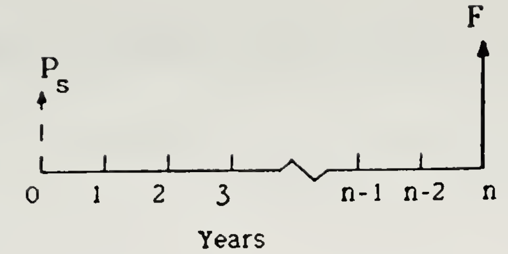
To compare a non-uniform series of costs of different projects, it is necessary to express the costs in common terms. One way to achieve this is to express them in an equivalent uniform series of payments often referred to as equivalent uniform annual cost (EUAC) [Grant et al. 1976]. Technically, when only agency costs are considered for life cycle cost analysis, the bridges considered should have the same level of service [FHWA 1987]. This condition, however, may not exist in many cases. At project level, this may not be a great problem, because a bridge may be expected to have the same level of service in terms of traffic volume range, even after an improvement. However, for a network level comparison of bridge projects, the analysis procedure

should be such that the difference in bridge traffic levels is appropriately considered.

4.4.2 Interest Formulas Required

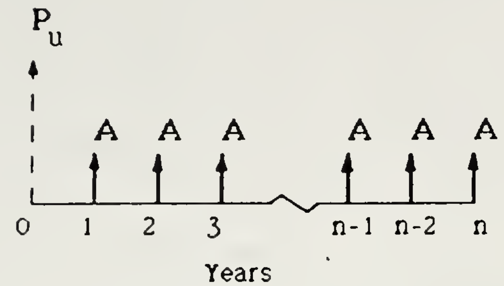
Five interest formulas may be needed to convert life cycle costs to the equivalent uniform annual costs. The first is the single payment present worth factor (SPPWF). This factor is used to convert single payment capital outlays in the future into a present worth, such as rehabilitation and replacement of a bridge at a future date. Figure 4.2-(a) illustrates how this factor is used. When a constant sum of money is spent at the end of each year for n years, as shown in Figure 4.2-(b), the total amount of the individual payments can be converted to a single present sum by using uniform series present worth factor (USPWF). If the uniform series payment does not start at the beginning of the project analysis period, its present worth obtained by USPWF needs to be discounted to the base year of the program period by using SPPWF. If expenditures would increase every year with a uniform arithmetic rate (G), such as a deck patching work, this uniform gradient series can be converted to the present worth by the gradient series present worth factor (GSPWF), as shown in Figure 4.2-(c). Again, if the start of the gradient series does not match the beginning of the analysis period, its present worth needs to be discounted to the beginning of the base year of the programming period. By using the above three interest formulas, life cycle costs can be discounted to the present worth and the total present worth of the alternate option can be determined.

The equivalent uniform annual cost (EUAC) over the service life is com-



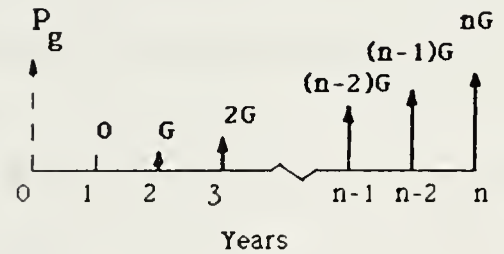
$$P_s = F\left[\frac{1}{(1+i)^n}\right]$$

(a) Single Payment Present Worth Factor



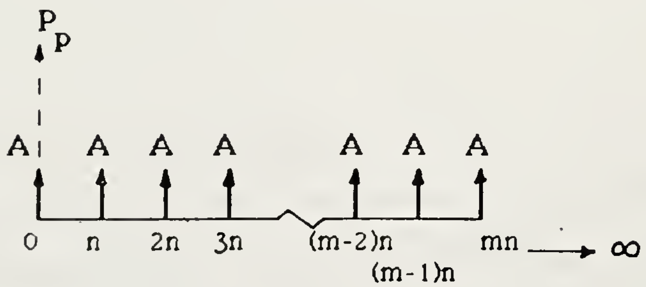
$$P_u = A\left[\frac{(1+i)^n - 1}{i(1+i)^n}\right]$$

(b) Uniform Series Present Worth Factor



$$P_g = \frac{G}{i}\left[\frac{(1+i)^n - 1}{i} - n\right]$$

(c) Uniform Gradient Series Present Worth Factor



$$P_p = A\left[\frac{(1+i)^n}{(1+i)^n - 1}\right]$$

(d) Perpetual Series with Multiples of n Years

Figure 4.2 Interest Formulas Needed to Compute Present Worth of Various Type of Payments

puted by multiplying the capital recovery factor (CRF) to the total present worth of a project. This factor converts a present amount based on some discount rate into a series of uniform annual payments for an n-year service life. The salvage value of a bridge can also be included, if desired. The salvage value can be converted to the present worth by using a SPPWF. Of course, the salvage value may be either a negative or positive cost depending upon the situation. In some cases, the salvage may be an income for the agency. In other cases, the agency may have to incur expenses to move the salvage away.

In general, bridges provide service to the traveling public in perpetuity. Therefore, it is necessary to compute EUAC for perpetual service. This is a case where "m" payments of an amount A are paid at "n" year intervals beginning in year 0 (zero date), as shown in Figure 4.2-(d). The amount A is the present worth of all costs incurred in one life cycle, and "n" is the service life. This cash flow series becomes a geometric power series that is convergent for i greater than zero [FHWA 1987]. For a perpetual series case, "m" is an infinite number. This factor is called the perpetual series present worth factor (PSPWF).

The formulas needed to compute the appropriate factors are summarized below:

$$SPPWF_{i,n} = \frac{1}{(1+i)^n} \tag{4.1}$$

$$USPWF_{i,n} = \frac{(1+i)^n - 1}{i(1+i)^n} \tag{4.2}$$

$$GSPWF_{i,n} = \frac{1}{i} \left| \frac{(1+i)^n - 1}{i} - n \right| \tag{4.3}$$

$$CRF_{i,n} = \frac{i(1+i)^n}{(1+i)^n - 1} \tag{4.4}$$

$$PSPWF_{i,n} = \frac{(1+i)^n}{(1+i)^n - 1} \tag{4.5}$$

where:

$SPPWF_{i,n}$ = single payment present worth factor at discount rate i (in decimals), over a period of n years;

$USPWF_{i,n}$ = uniform series present worth factor at discount rate i, over a period of n years;

$GSPWF_{i,n}$ = gradient series present worth factor at discount rate i, over a period of n years;

$CRF_{i,n}$ = capital recovery factor at discount rate i, over an analysis period of n years; and

$PSPWF_{i,n}$ = perpetual series present worth factor at discount rate i, with n equal payment intervals.

4.4.3 Repeatability and Perpetuity

When a bridge is either replaced or rehabilitated, it eventually comes to the end of its service life and it needs to be replaced again. It is impractical to try to determine precisely what type of bridge works would be needed in the distant future, say 30 to 40 years ahead. Therefore, it is a common practice in life cycle cost analysis to assume a certain sequence of maintenance and rehabilitation works. After the first replacement, the same work

sequence is assumed to repeat itself in perpetuity [FHWA 1987], as shown in Figure 4.3. Even if a rehabilitation work is performed, the bridge is eventually replaced and its life cycle activity profile is repeated. In such a case, the rehabilitation cost is considered to be capitalized, that is, the present worth of rehabilitation related expenditures is amortized in perpetuity. The EUAC in perpetuity is thus computed by multiplying the present worth of all costs by the interest rate in decimals [Weyers et al. 1983]. The use of perpetual service of a bridge is based on the fact that bridge sites are normally used for a long period of time (50 years or more) [FHWA 1987].

4.4.4 Interest Rate and Inflation

In choosing among alternative investment proposals, it is desirable in principle to make an analysis in unit of constant purchasing power. Usually, inflation is excluded from the prevailing discount rate. Cost inputs estimated at present prices are used for life cycle cost analysis and all monetary items are given in constant dollars.

In case the rate of inflation outgrows the rate of income in program funding, the effect of inflation may affect investment decisions, because the effective discount rate would be different. The interest rate under this situation can be expressed in the following interest formula [Cady 1983]:

$$i^* = \frac{(1+i)(1+q)}{(1+f)} \tag{4.6}$$

where,

f = expected rate of inflation

q = expected rate of increase in highway funding,

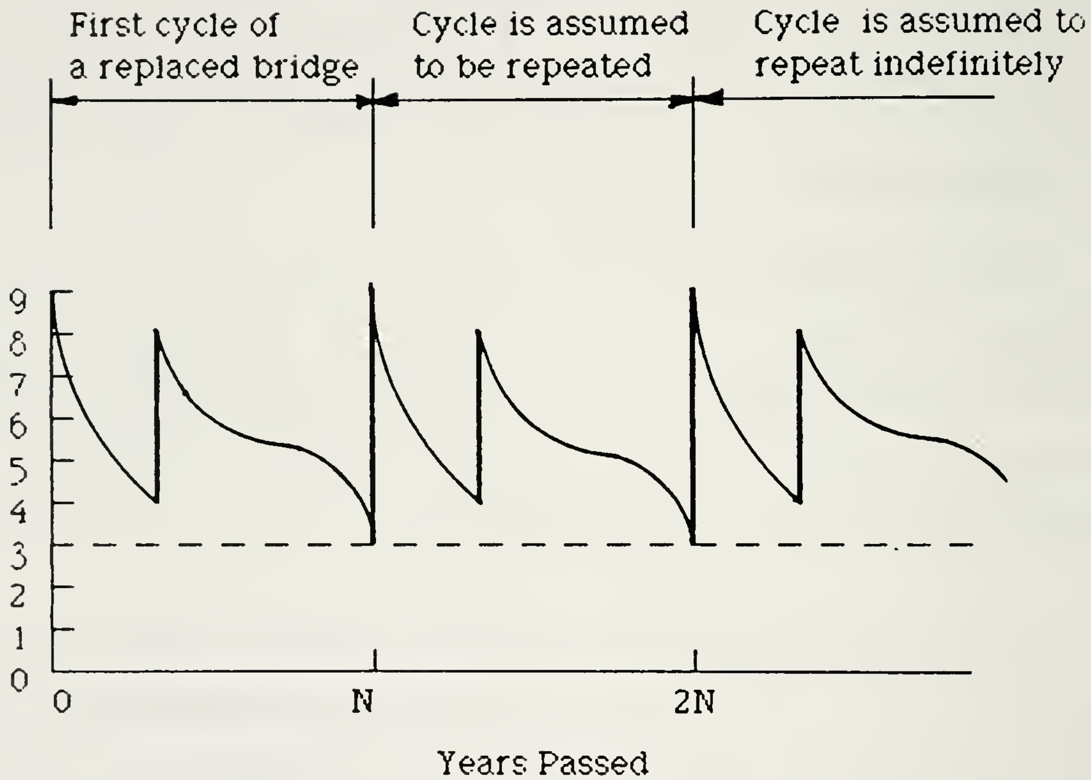


Figure 4.3 Repeatability and Perpetuity Assumptions

i = prevailing discount rate,

i^* = "true" discount rate that incorporates the effect of inflation.

This formula suggests that the "true" interest rate is a function of three factors: prevailing interest rate, inflation rate, and rate of increase in funding. If the rate of increase in funding is expected to keep pace with the rate of inflation, the discount rate can be taken to be equal to the prevailing discount rate.

It can be argued, however, whether it could be justified to include rates of great uncertainty, such as rate of inflation and rate of increase (or decrease) in highway funding, into an analysis that projects many years into the future. Further, when two factors are included in the interest formula, their rates will be fixed throughout the analysis period. Therefore, rather than using uncertain factors, it may be better to use a "best estimate" of discount rate on the basis of current economic conditions at the base year.

Another way of possible consideration of inflation may be to use inflated future costs. Although this method seems realistic, it is a difficult task to perform. First, it is necessary to estimate the purchasing power of money in future years. Second, cost data usually available at hand are the costs in the current year or they are the ones which have been obtained by analyzing cost data of previous years. It is difficult, if not impossible, to estimate the differential effects of future inflation on various cost categories. A reasonable approach to estimate the effect of inflation is to perform a series of sensitivity analysis with various discount rates as well as by varying rates of inflation and program fund increase.

4.5 Application of Life Cycle Cost Analysis to Bridge Management

Two levels of application can be made: project level and network level. Figure 4.4 illustrates a series of steps that needs to be followed for a project level analysis, where the purpose is to select the least cost option for a single bridge. To implement the life cycle cost analysis as part of the proposed bridge management system, a temporary database is created. Only the variables needed for the analysis are transferred from the bridge management database to this temporary data base. Remaining data fields of this temporary file store life cycle costing data and the computed equivalent uniform annual costs.

In order to perform a life cycle cost analysis, it is necessary to construct a life cycle activity profile. A set of pre-determined activity profiles can be prepared for recommended improvement options for immediate use. Or, an option can be given so that life cycle activity profile can be interactively constructed. Results of the analyses conducted in the present study on costs and timings of improvement works can be useful in constructing life cycle activity profiles and making estimates of future improvement costs. Once the equivalent uniform annual costs for the options for a bridge site are computed, they are used to choose the least cost option for the particular bridge site.

Figure 4.5 gives the steps for making a network level comparison for selecting a set of cost-effective bridge projects at different sites. After the projects with least equivalent uniform annual costs at individual bridge

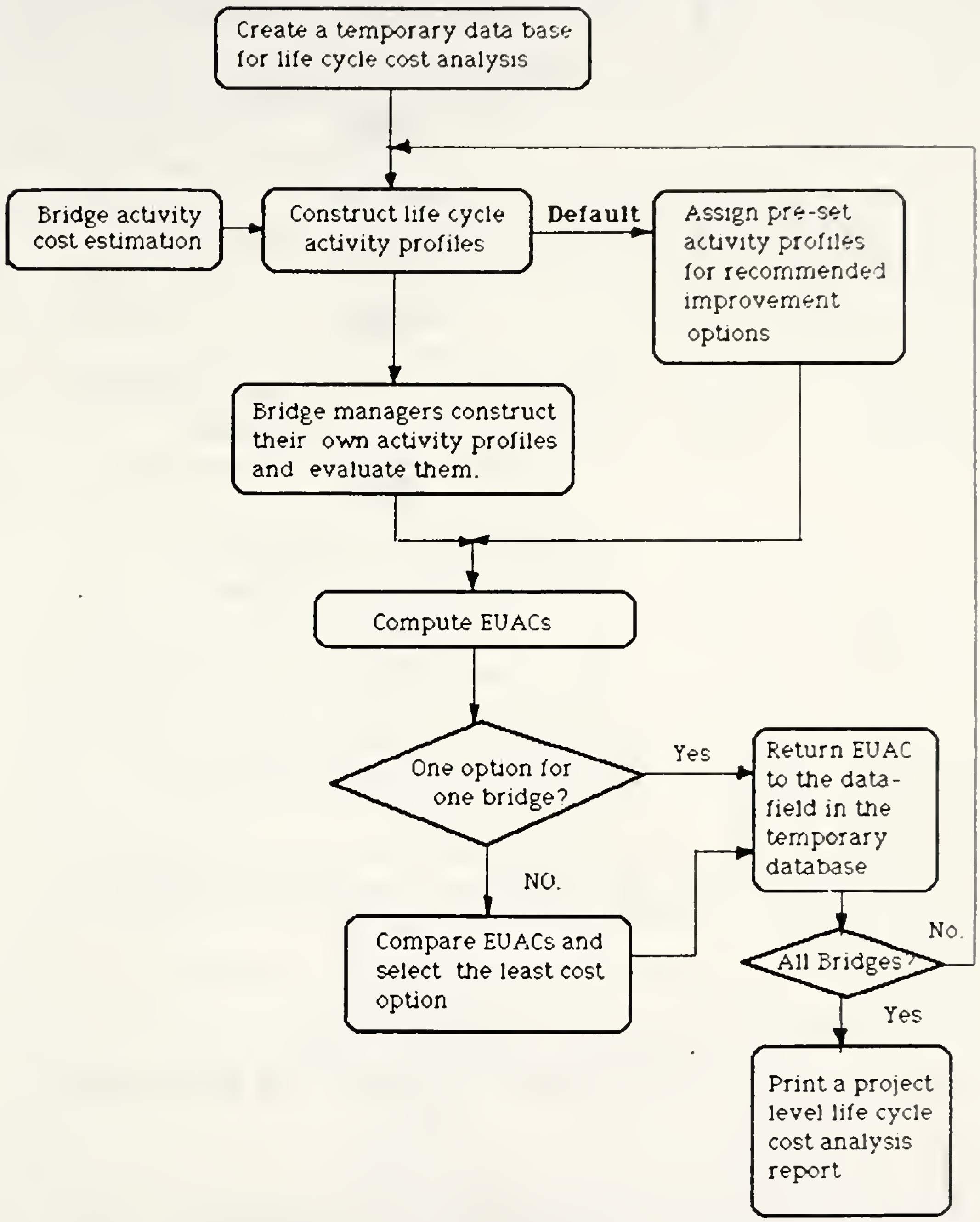


Figure 4.4 Flow Chart of Project Level Life Cycle Cost Analysis

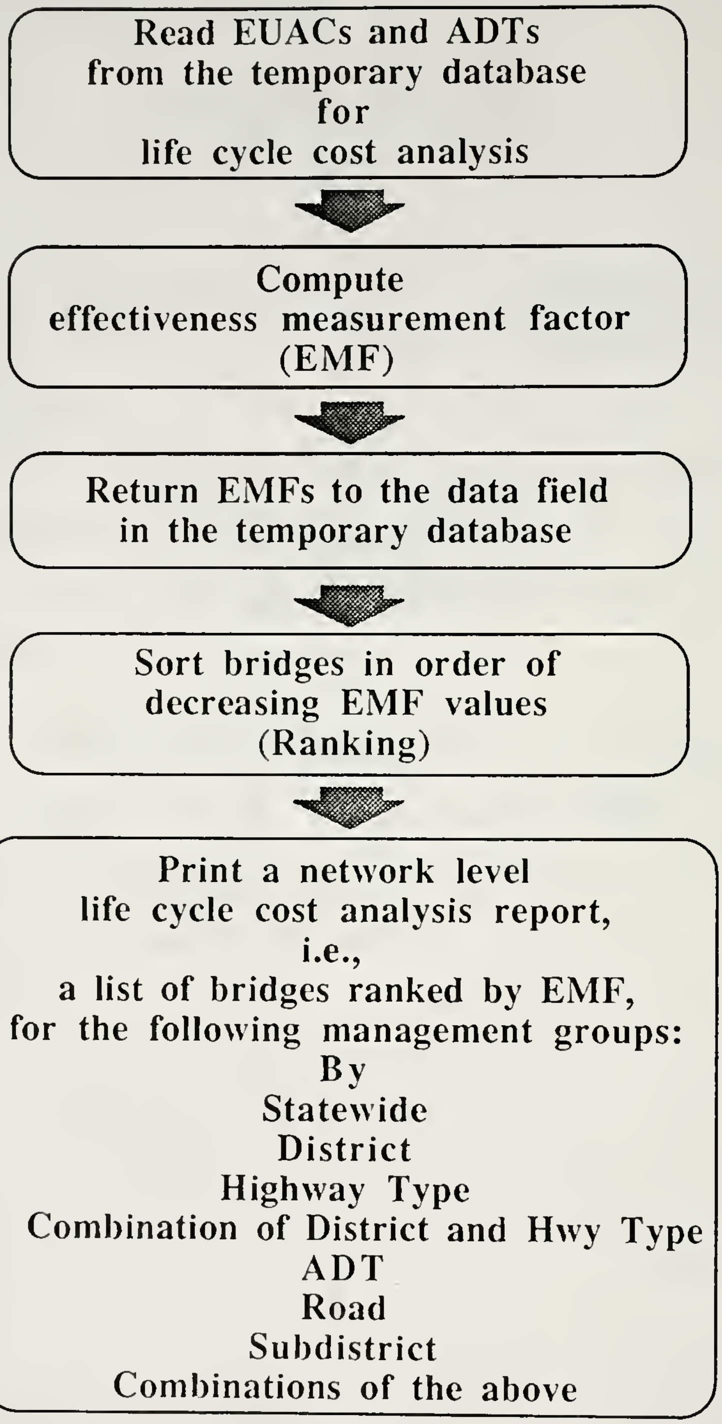
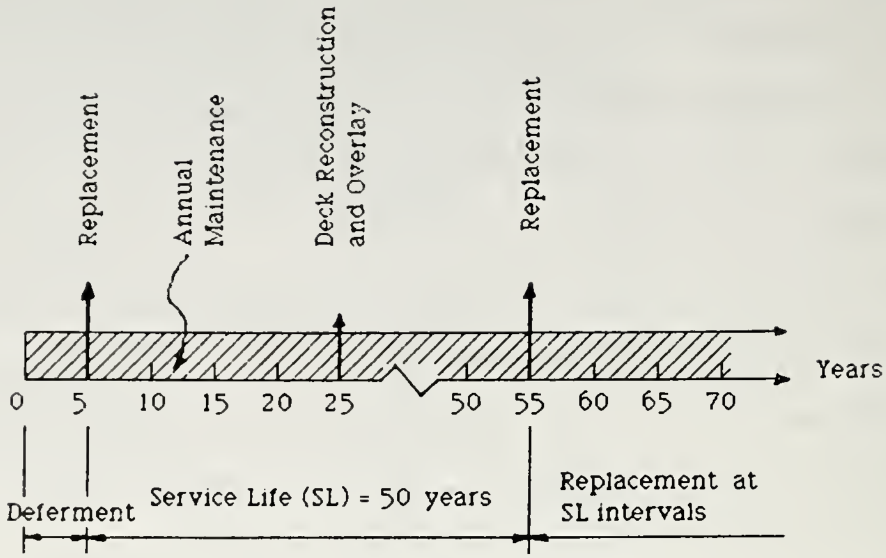


Figure 4.5 Steps for Making Network Level Project Comparisons

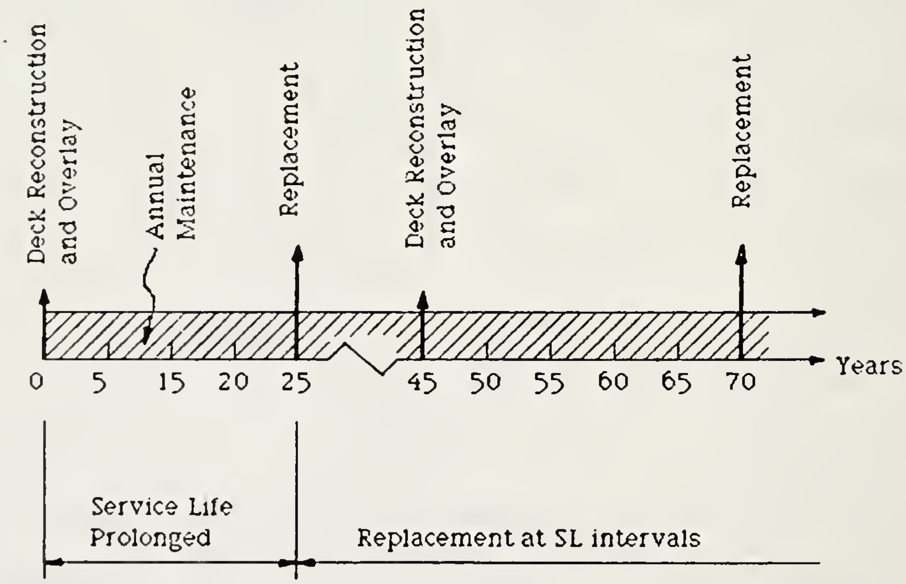
sites are determined, the information is stored in the temporary data base. Because the service levels of various bridges are different, the equivalent uniform annual cost method cannot be directly used for making a network level comparison. It is necessary to have a normalizing factor that would reduce the difference of service levels among the bridges. A factor called "effectiveness measurement factor" was developed in this study. This factor computes the number of vehicles served by one dollar of investment, as discussed in a later section of this chapter. Projects can be ranked as a whole or by group, such as highway type and district.

4.5.1 Constructing Life Cycle Activity Profile

In order to perform a life cycle cost analysis, it is necessary to construct a life-cycle activity profile. A life cycle cost profile can be developed based on the knowledge of bridge history and bridge condition deterioration curves. The activity profile can provide a good estimate of expected future costs, although it is unlikely that the amount and timing of future expenditures will exactly follow the projected profile. Three basic pieces of information must accompany each bridge activity profile: cost, starting time of bridge works, and duration of bridge works. Figure 4.6-(a) gives a sample life cycle activity profile for a replacement option with five year deferment, and Figure 4.6-(b) shows a case of an immediate major rehabilitation which would extend the remaining service life of the bridge by twenty years. The construction of life cycle activity profiles can be done either by default assignment from a set of pre-determined profiles, given some selection criteria such as type and timing of the next recommended bridge work, or by the bridge manager based on his engineering judgments. Once the proposed



(a) Life cycle activity profile for replacement with 5 year deferment



(b) Life cycle activity profile for immediate rehabilitation

Figure 4.6 Sample Life Cycle Activity Profiles

bridge management system is started and bridge activities are clearly defined, unique identification codes should be assigned to them so that their cost information can be readily extracted from the cost data file in the future.

4.5.2 Computing Estimated Cost for Planned Bridge Work

Once alternative life cycle activity profiles are defined for a bridge, it is necessary to determine estimates of costs which may be occasioned by the bridge activities included in the profiles. The results of maintenance, rehabilitation, and replacement cost analyses discussed in Chapter 2 can be used for this purpose. Tables 4.1 and 4.2 illustrate steps which can be followed to make estimates of future costs using the results of the present study.

Table 4.1 gives a sample computation for a replacement option. Cost data for a replacement option are available for four cost components: superstructure, substructure, approach construction, and other miscellaneous items. As for superstructure and substructure costs, unit costs are available for four superstructure type groupings, as shown in Tables 2.6 and 2.7. Regression models of these costs are also available in Table 2.14. In the example, regression models for all cost components were used. Other tables and figures used in this computation and the variables needed for the regression models are also shown in Table 4.1.

Table 4.2 shows a sample computation for an immediate rehabilitation option. Rehabilitation costs consist of two parts: the bridge item cost and the "other" cost. The bridge item cost is used by INDOT as a sum total of costs directly needed for a rehabilitation activity. It is given by dollars spent per square foot of deck area. The "other" cost includes all other costs

Table 4.1 Computation of Estimated Life Cycle Activity Costs for Bridge Replacement Option

Data of a New Bridge

Bridge Type	: Box-beam superstructure with pile-type substructure
Structure Length (BL)	: 100 ft.
Deck Width (DW)	: 46 ft.
Approach Length (APL)	: 1,000 ft
Earthwork (EW)	: 2,500 yd^3
Vertical Clearance (VC)	: 25 ft.

(a) Replacement Cost

* Superstructure Cost (Table 2.14) $= 0.0137(BL)^{1.001}(DW)^{1.161}$ = \$117,300
* Substructure Cost (Table 2.14) $= 0.00354(BL)^{0.744}(DW)^{1.205}(VC)^{0.515}$ = \$ 57,600
* Approach Cost (Table 2.15) $= 4.715(APL)^{0.403}(EW)^{0.250}$ = \$170,000
* Other Cost (Table 2.16) $= 0.0721(BL)^{0.696}(DW)^{0.932}$ = \$ 63,000

Total Replacement Cost = \$407,900

(b) Rehabilitation Cost at 25th Year (Deck Reconstruction & Overlay)

* Bridge Item Cost (Table 2.22-(a)) = $(12.62\ \$/ft^2)(BL)(DW)$ = \$ 58,000
* Other Cost (Table 2.24-(b)) = 58,000 x 1.2331 = \$ 71,500

Total Rehabilitation Cost = \$129,500

(c) Maintenance (Routine Maintenance)

* Hand Cleaning of Deck (Annual) (Figure 2.13) = $(51.26\ \$/ft^2)(BL)(DW)/549.1$ = \$ 400/year
* Deck Flushing (Figure 2.14) = $(34.14\ \$/ft^2)(BL)(DW)/549.1$ = \$ 300/year
* Bridge Repair, Deck Patching, & Others (Assumed) (Table 2.31) = \$ 800/year

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Total Maintenance Cost = \$1,500/year

Table 4.2 Computation of Estimated Life Cycle Activity Costs for Immediate Rehabilitation Option

Data of the Existing Bridge

Bridge Type	: Box-beam superstructure with pile-type substructure
Structure Length (BL)	: 90 ft.
Deck Width (DW)	: 40 ft.
Expected Remaining Life	: 20 years

(a) Rehabilitation Cost (Deck Replacement with Related Repairs)

* Bridge Item Cost (Table 2.26-(a)) = (42.02 $/ft^2)(BL)(DW) = $151,300
* Other Cost (Table 2.26-(b)) = 151,300 x 1.1395 = $172,400

Total Rehabilitation Cost = $323,700

(b) Replacement at the End of 20th Year

Assume that the same life cycle activity profile for replacement in Table 4.1 will begin at this point.

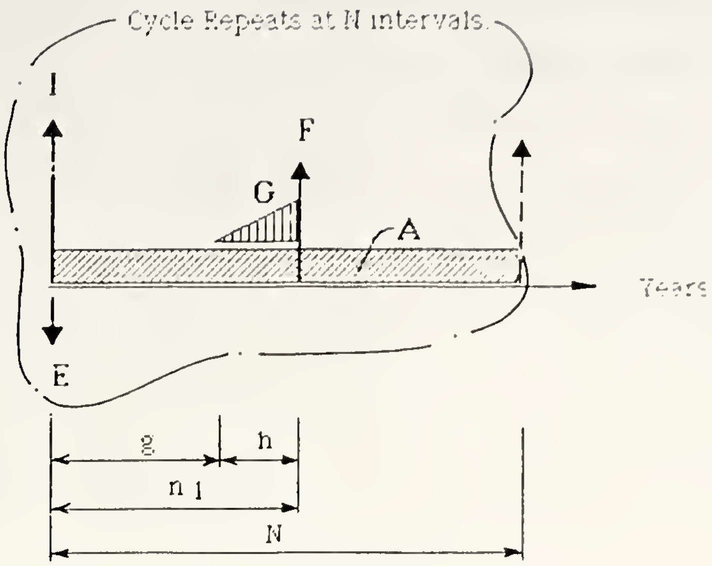
related to rehabilitation work, such as traffic maintenance, mobilization, and demolition. The other work is expressed as the percentage of the bridge item cost.

Maintenance costs are given in unit costs in terms of measurement units defined in the Field Operation Handbook for Foremen [1985-86]. Unit costs were computed for the five routine maintenance activities currently conducted by INDOT maintenance forces. Other maintenance activities were considered in rehabilitation costs. Once the module for recording and monitoring of bridge activities suggested for the IBMS is implemented with more precise maintenance work groupings, more reliable unit costs of maintenance works would be available.

All costs given in Chapter 2 are in 1985 dollars. When the base year of the life cycle cost analysis is not 1985, it is necessary to update these costs. One method is to multiply the cost figures by the ratio of the FHWA structure construction price index [BOC 1986] for the project year to the same index for 1985.

4.5.3 Computing Equivalent Uniform Annual Cost

Once a life cycle activity profile is established and estimated costs for the planned activities are estimated, the uniform annual cost for this profile can be computed. A simple example is discussed to explain the procedure. Figure 4.7 shows an activity profile of an immediate replacement option and a general formula to compute its EUAC. All future maintenance, rehabilitation, and replacement expenditure are converted to a present value by multiplying appropriate factors (SPPWF, USPWF, GSPWF) with a discount rate and analysis



$$EUAC_{\substack{\text{replacement}\\ \text{in perpetuity}}} = [\{I - E + G(GSPWF_{i,h+1})(SPPWF_{i,g-1}) + F(SPPWF_{i,n_1}) + A(USPWF_{i,N})\}(PSPWF_{i,N})]i$$

where I = initial replacement cost
F = future rehabilitation cost
A = annual maintenance cost
G = gradient series of maintenance cost increase due to progressive deterioration
E = salvage value of existing structure
g = time passed before the beginning of uniform gradient series of maintenance cost increase
h = duration of uniform gradient series maintenance cost increase
n_1 = time passed before the future rehabilitation
N = life of replaced new bridge
i = discount rate
SPPWF = single payment present worth factor
USPWF = uniform series present worth factor
GSPWF = gradient series present worth factor
PSPWF = perpetual series present worth factor

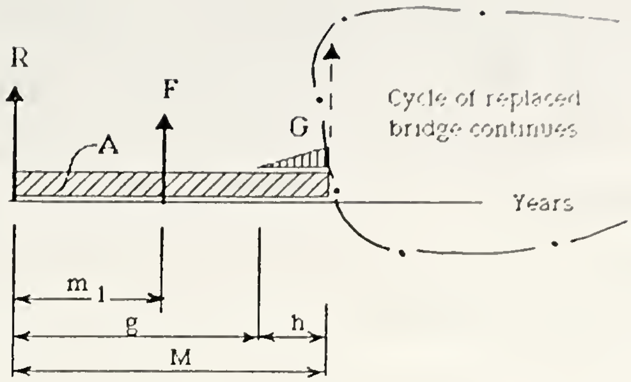
Figure 4.7 Sample Perpetual EUAC for a Replacement Option

period. An appropriate analysis period needs to be determined. Results of the analysis on timings of bridge activities discussed in Chapter 3 can be used. This amount represents the present worth of bridge replacement cost for one life cycle. Considering future bridge replacements at periodic intervals (N) in perpetuity, the present worth of all replacement costs can be computed by multiplying PSPWF with the present worth of bridge replacement for one life cycle. The EUAC of bridge replacement in perpetuity can then be computed by multiplying the present worth of periodic bridge replacement costs with the discount rate.

In Figure 4.7, the variable "I" stands for the initial replacement cost, "F" for a future major rehabilitation cost, and "E" for the salvage value of the existing structure. Annual constant maintenance cost is expressed as "A", and maintenance costs that are considered to increase every year are expressed as "G".

When maintenance and rehabilitation options are chosen for an immediate action, the need for future bridge activities does not end there. A bridge will have to be replaced entirely sometime later. Figure 4.8 shows a sample activity profile for an immediate rehabilitation case. In this case, the bridge is expected to be replaced at the end of M years, and therefore, the perpetualized replacement costs, properly discounted to the present time by SPPWF, needs to be added to the maintenance and rehabilitation costs. Costs required up to the eventual bridge replacement should be considered to be capitalized [Weyers et al. 1983].

Salvage values can be included, if desired. However, salvage values are



$$EUAC_{\substack{\text{rehabilitation}\\ \text{in perpetuity}}} = [(\text{Present Worth of Periodic Replacement Costs})(SPPWF_{i,M})$$

$$+ (\text{Present Worth of Costs during the Extended Life})]$$

$$= [(\text{Present Worth of Periodic Replacement Costs})(SPPWF_{i,M}) + R$$

$$+ F(SPPWF_{i,m_1}) + G(GSPWF_{i,h+1})(SPPWF_{i,g-1}) + A(USPWF_{i,M})]i$$

where R = initial rehabilitation cost
F = future rehabilitation cost
A = annual maintenance cost
G = gradient series of maintenance cost increase due to progressive deterioration
E = salvage value of existing structure
g = time passed before the beginning of uniform gradient series of maintenance cost increase
h = duration of uniform gradient series maintenance cost increase
m_1 = time passed before the future rehabilitation
M = extended life of the existing structure
i = discount rate
SPPWF = single payment present worth factor
USPWF = uniform series present worth factor
GSPWF = gradient series present worth factor

Figure 4.8 Sample Perpetual EUAC for a Rehabilitation Option

unlikely to have a significant impact on the outcome of economic analyses [Wonsiewicz 1988]. Therefore, it is suggested that salvage values be not included in the analysis because it may not prove to be fruitful to spend efforts on their estimates.

4.5.4 Comparing Alternative Options

It should be noted that since only agency costs are included in the life cycle cost analysis at present, the comparison of alternative options on the basis of this analysis should be made only for bridges which have similar type, size, and performance as a result of the recommended bridge activities. For a project level analysis, the procedure can be directly used to compare two or more alternative options, because the bridge characteristics remain essentially the same after any of the options is implemented. However, at network level, the physical size and level of service of different bridges would rarely be the same. Therefore, a weighting factor which can overcome this problem needs to be defined for comparing multiple bridge improvement projects selected for different bridge sites.

4.5.4.1 Project Level Analysis

The computation of the equivalent uniform annual costs for various options at individual bridge sites is the first step of a life cycle cost analysis. When two alternative activity profiles are compared for a single bridge, their EUACs can be used to select the least cost option. Decision of selecting either rehabilitation or replacement takes place when bridges are rather old and close to the end of their service lives. No bridge inspector would recommend a replacement of the entire bridge structure, when its age is

about 20 years, unless the bridge is severely damaged by distresses or the bridge needs to be widened. According to the data collected during the study, bridges were replaced when their ages were 53 years on the average. On the other hand, the most popular rehabilitation category, the deck reconstruction and overlay work, was done when bridges were about 22 years old, on the average. The second common major rehabilitation work, deck replacement, was done when bridges were near 45 years, as discussed in Chapter 3. It must be noted that the data set for replacement and that for rehabilitation were different and the figures indicate only averages. Consequently, it cannot be assumed that one overlays a bridge at 22 years, replaces the deck at 45 years and then replaces the bridge at 53 years.

A critical decision is to determine the timing for either a replacement of the entire bridge or the deck. The deck replacement option, which usually includes some repairs to superstructure and substructure at the same time, rarely takes place unless the bridge service life can be significantly prolonged by this option. Data collected in the present study indicated that once the deck was reconstructed, it would rarely be replaced in the future although it may be reconstructed later. On the other hand, bridges which had deck replacement would rarely have a deck reconstruction work before a deck replacement.

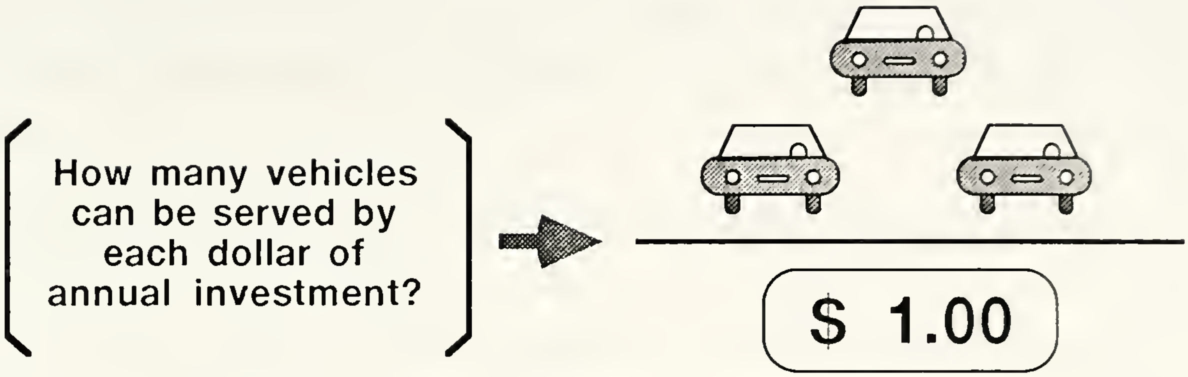
The following general comments can be made regarding the timing of bridge improvement options. When a bridge age is relatively less, say, less than 40 years, the question would be the choice of either deck reconstruction or deck replacement, depending on the prevailing distress conditions. If the bridge age is less than 20 years, then there would be only one improvement action

recommended, which is a deck reconstruction. The deck replacement activity is an expensive option and it is doubtful that the inspector would ever recommend such a drastic measure unless the deck is severely damaged or distressed, or it needs to be widened. The opportunity of selecting either deck replacement or deck reconstruction would take place most probably between the bridge age of between 20 and 40 years. After the bridge age of 40 years, three alternatives may be considered, depending on the degree of distresses observed on the structure: deck reconstruction, deck replacement, and bridge replacement.

4.5.4.2 Network Level Analysis

When multiple bridges are compared at the network level for selecting bridges for the next programming period, EUACs computed by the life cycle cost analysis cannot be directly used because the bridges are not of homogeneous characteristics and performance. In order to make the costs commensurable, EUAC values need to be appropriately adjusted. The most direct adjustment factor can be the traffic volume associated with each bridge. In the present study, the EUAC was converted into an effectiveness measurement factor (EMF) by dividing the annual bridge traffic volume by EUAC (365ADT/EUAC), as shown in Figure 4.9. The implied meaning of EMF is the number of vehicles expected to benefit from each dollar to be spent on a bridge activity.

In addition to the use of equivalent uniform annual cost of all expenditures, the state or federal funding portion of the equivalent uniform annual cost can also be separately considered. Federal funding proportions for capital investment projects are up to 90% for interstate and up to 75% for primary, secondary, and urban highways. Bridges on federal-aid primary, secon-



$$\mathbf{EMF} = \frac{365\ (\mathrm{ADT})}{\mathrm{EUAC}}$$

Figure 4.9 Effectiveness Measurement Factor for Network Level Project Comparison

dary, and urban highways can receive up to 80% of federal subsidy, instead of 75%, if replacement or rehabilitation is recommended according to the criteria of the federal bridge rehabilitation and replacement funds. A bridge replacement project with sufficiency rating of less than 50 is eligible for 80% federal funding. A rehabilitation project must have a sufficiency rating which is equal to or greater than 50 and less than 80 to receive 80% funding. If these conditions are not met, the federal funding proportion returns to 75%.

Ranking of bridge projects at network level can be done by the EMF if only the least cost option is to be used. Sorting is performed using the EMF to determine which bridge projects would serve the most highway users for each dollar spent for bridge work. This ranking procedure may place preference to the bridges that carry a large ADT. Consequently, bridges on interstates or primary highways may be favored. Therefore, care should be taken in using the procedure. For example, in order to reduce the bias, bridges can be first grouped into homogeneous categories by using factors, such as highway type, district, or a combination of district and highway type, and then their EMFs can be computed for selection of projects from each group. However, in this case, a procedure would be needed to subdivide the total available funds among the categories before the selection can proceed.

4.5.5 Preparing Reports

A report that can be made for a project level life cycle cost analysis may include a table listing bridge types, timings, and costs of bridge works included in the life cycle activity profile for a single bridge. It can also

include the resultant equivalent uniform annual cost for perpetual service of the life cycle activity profiles studied.

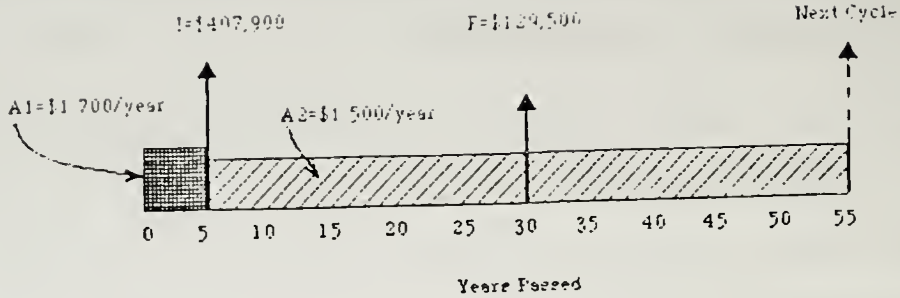
On the other hand, a report for a network level comparison may include a list of bridge projects, which is a collection of the least cost options for individual bridges, ranked in descending order of the effectiveness measurement factor (EMF). Reports can be individually produced by using a sorting routine for certain groups of bridges such as district, highway type, or a combination of district and highway type.

4.6 Sample Applications

To demonstrate the calculation procedure of life cycle cost analysis as applied to bridge management, three examples are presented. First two examples illustrate cases of a project level analysis and the third example shows a case of network level analysis. A discount rate of 5% was used in these sample computations.

4.6.1 Project Level Analysis with One Improvement Option

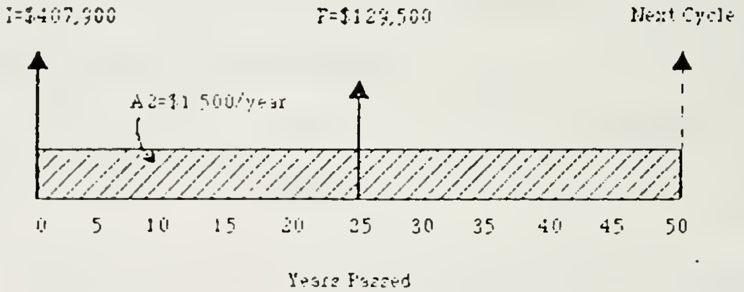
In this case, a bridge replacement option is being considered with two different timings. The bridge is in poor condition, and an immediate replacement is desirable. However, if necessary for financial and other reasons, the replacement can be deferred for 5 years. Figure 4.10 illustrates the life cycle activity profiles and the computational procedure to obtain the equivalent uniform annual cost for perpetual service. The zero date is the beginning of the programming year. The cash flow diagrams in the figure show the timings and costs of replacement and maintenance works. The salvage value



$$\mathrm{EUAC}_1 = 0.05[1{,}700(\mathrm{USPWF}_{0.05,5}) + (\text{Present Worth of Deferred Periodic Replacement Costs at the Time of 1st Replacement})(\mathrm{SPPWF}_{0.05,5})]$$

$$= 0.05[1{,}700(\mathrm{USPWF}_{0.05,5}) + (\mathrm{PSPWF}_{0.05,50})\{407{,}900 + 129{,}500(\mathrm{SPPWF}_{0.05,25}) + 1{,}500(\mathrm{USPWF}_{0.05,50})\}(\mathrm{SPPWF}_{0.05,5})]$$

$$= \$20{,}691$$



$$\mathrm{EUAC}_0 = 0.05[\text{Present Worth of Periodic Replacement Costs}]$$

$$= 0.05[(\mathrm{PSPWF}_{0.05,50})\{407{,}900 + 129{,}500(\mathrm{SPPWF}_{0.05,25}) + 15{,}00\ (\mathrm{USPWF}_{0.05,50})\}]$$

$$= \$25{,}938$$

Legend:
- A_1 = Maintenance cost during deferment
- A_2 = Maintenance cost after replacement
- F = Deck reconstruction and overlay cost
- I = Bridge replacement cost
- EUAC_1 = Equivalent uniform annual costs in perpetuity for deferred replacement option
- EUAC_0 = Equivalent uniform annual costs in perpetuity for immediate replacement option

Figure 4.10 Sample Calculation for a Single Bridge with Immediate and Deferred Replacement Options

of the existing bridge is assumed to be nil. As shown in the example, the bridge would still need routine maintenance until it is replaced. The economic gain of not replacing the bridge immediately is \$(25,938 - 20,691) or \$5,247 per year in perpetuity. If functionally adequate and if structurally within acceptable limit, the bridge replacement can be deferred for five more years and the funds can be used for more critical needs.

4.6.2 Project Level Analysis with Two Improvement Options

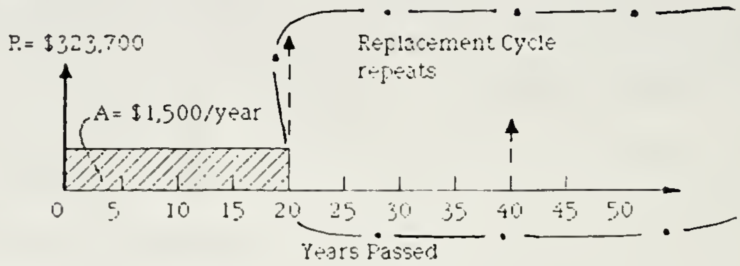
The second example shows a case where the existing bridge is 40 years old and the deck is essentially in bad condition. The inspector recommends two possible options: deck replacement and bridge replacement. He estimates that the bridge service life after deck replacement would be twenty years, because the substructure is still in fair condition to support traffic loadings for the duration of the extended service life. Figure 4.11 presents the data and and related computations. For the replacement option, the activity profile shown in Figure 4.10 is used. The activity profile for the rehabilitation option consists of the extended service life period which contains the deck replacement and maintenance work. The equivalent uniform annual cost of the deck replacement option is \$26,895 per year in perpetuity. By comparing the EUACs of the deferred bridge replacement and immediate deck replacement options, it is obvious that it is economically more desirable to defer the bridge replacement for five years and not to replace the bridge deck.

In this case, the difference between the EUACs of the two options was greater than 10%. When the difference of the EUACs is less than 10%, caution should be used in selecting a preferred option. A sensitivity analysis is

* Option 1 - Bridge replacement after 5 year deferment

$$EUAC_{\substack{\text{deferred}\\ \text{replacement}}} = \$20{,}691$$

* Option 2 - Immediate replacement of bridge deck



Legend: R = Immediate deck replacement cost
A = Maintenance cost throughout the extended service life

$$EUAC_{\substack{\text{immediate deck}\\ \text{replacement}}} = 0.05[(\text{Present Worth of Deferred Periodic Replacement Costs at the Time of the First Replacement})(SPPWF_{0.05,20}) + 323{,}700 + 1{,}500(USPWF_{0.05,20})]$$

$$= \$26{,}895$$

Figure 4.11 Sample Calculation for a Single Bridge with Two Improvement Options

Table 4.3 Comparison of Bridge Projects by Effectiveness Measurement Factor

Bridge No.	Highway Type	ADT*	Improvement Option	EUAC ($/year)	EMF ** (veh/$)	Rank
1	Primary	8,000	Bridge replacement with 5 year deferment	$19,632	149	3
2	Primary	11,000	Deck replacement	$22,830	175	2
3	Primary	6,000	Deck rehabilitation	$17,500	125	4
4	Primary	13,000	Deck rehabilitation	$24,775	191	1

Note: * Average Daily Traffic (veh/day)

** Effectiveness Measurement Factor = (365) (ADT)/EUAC

recommended by varying parameters such as discount rate, deferment period, and cost and timing of future bridge works.

4.6.3 Network Level Analysis with Multiple Projects

Before performing a network level comparison of projects, it is necessary to perform a project level analysis first and select the least cost option for each bridge location. In Table 4.3 an example of four bridges is given indicating the average daily traffics and EUACs for least cost options. The effectiveness measurement factor (EMF) for each bridge project is also presented. It can be seen that the bridge project number 3 would have been selected first, bridge project number 1 second, bridge project number 2 third and bridge project number 4 fourth, if EUAC value were the only evaluation criterion. However, when the average daily traffic is included, the bridge project number 4 gets the highest priority and bridge project number 3 the lowest. The bridge project number 4 can serve most vehicles per dollar spent than the other options. It should be noted that this is only a guide for ranking bridge projects. The final selection of bridge projects need to be made after careful consideration of other ranking factors.

4.7 Chapter Summary

A procedure to perform a life cycle cost analysis on bridge improvement options was discussed in this chapter. Because bridges are a long-term investment, the consideration of life cycle costs is essential to evaluate economic desirability of an option over the others. The equivalent uniform annual cost (EUAC) method for perpetual service was used in this study, because this method is especially suitable for evaluating multiple

alternatives with different analysis periods. Only agency costs were included in the life cycle cost analysis, because user costs associated with bridge projects have not yet been clearly quantified in monetary terms.

For the application of the life cycle cost analysis, either pre-constructed activity profiles can be used or a bridge manager can input his own activity profiles. The life cycle cost analysis constitutes a sub-module of the project selection module of the Indiana bridge management system (IBMS). In order to construct reliable life cycle activity profiles in the future, the implementation of the recording and monitoring module of the IBMS is essential, as discussed in Volume 1 of this report.

For selecting a group of least cost options from different bridge locations, equivalent uniform annual costs need to be converted to commensurable values. For this purpose, bridge traffic volumes were used as a weighing factor. The factor indicates the number of vehicles benefited for each dollar spent on a bridge activity. Another approach can be to take the deck area as a normalizing factor so that large bridges do not end up being in a deferred category. The resultant list of ranked bridges can be used as a guide to select bridge projects for the next programming period. The final decision, however, must be made taking into account all relevant management factors.

CHAPTER 5

SUMMARY AND CONCLUSIONS

As part of the study to develop a comprehensive bridge management system for the Indiana Department of Transportation, a detailed analysis of bridge maintenance, rehabilitation, and replacement costs was conducted, and a procedure for life-cycle cost analysis was developed. A computer program for cost analysis was coded in FORTRAN 77, which incorporated all the results and methodologies presented in this report.

The life-cycle cost analysis sub-module would allow the bridge manager to evaluate what type of improvement activity would be recommended for achieving the least overall annual cost for a bridge. At present, only the agency cost can be considered in the analysis; however, as the program matures and necessary data are collected, the highway user costs can be included. The recommended life-cycle cost analysis would use the equivalent uniform annual cost (EUAC) for perpetual service of an estimated life-cycle activity profile. For statewide analysis, the cost figures can be weighed by annual average daily traffic values. Alternatively, deck area can also be used as a normalizing factor.

5.1 Summary of Findings

Statistical analyses were done to develop unit costs for maintenance,

Statistical analyses were done to develop unit costs for maintenance, rehabilitation and replacement projects. Actual bid costs were used in the analyses and the costs of different years were converted to the 1985 price using the construction index of the FHWA related projects [BOC 1986]. Analyses were also done to determine the timing for undertaking bridge replacement and major rehabilitation activities.

Replacement costs were found to be affected mostly by the types of superstructure and substructure. Currently, replacement costs are grouped by a combination of superstructure type and highway class. But, it was found that highway class would not significantly affect unit structure costs of new bridges.

Analyses of rehabilitation costs considered the two major tasks: deck reconstruction and deck replacement. Most of the bridge rehabilitation tasks in Indiana included bridge decks. A host of other superstructure and substructure works are also included as part of deck rehabilitation projects. The current categorization of bridge rehabilitation works in INDOT would not be specific enough for a detailed life cycle cost analysis. A new list of rehabilitation groups was thus suggested.

Maintenance cost analyses were done using subdistrict average values. Unit maintenance costs were developed for the five routine maintenance activities currently undertaken. Two of the current routine maintenance activities (bridge repair and other bridge maintenance categories) are used to record many types of activities. Some of them can be recorded separately because the high frequency of their occurrence. A new list of routine maintenance activi-

ties was suggested to make the recording of future maintenance work more precise than the existing one.

Analyses on timing of replacement and rehabilitation showed that the decision to replace or rehabilitate was statistically independent of traffic volume. Deck reconstruction work was done, on the average, when a bridge was approximately 22 years and deck replacement was done, on the average, when a bridge was approximately 45 years, if no deck reconstruction had been done. Although the timing of these works would be affected by the policy and the availability of funds, the results of the analysis provide an overall guideline as to bridge activity profiles. For instance, up to the bridge age of about 20, deck reconstruction would be the most frequently used option. When the age advances to about 40 years, the choice would be between deck reconstruction and deck replacement. As age advances further, say, 50 years, the choice would be among deck reconstruction, deck replacement, or bridge replacement, depending on the conditions of deck, superstructure, and substructure.

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